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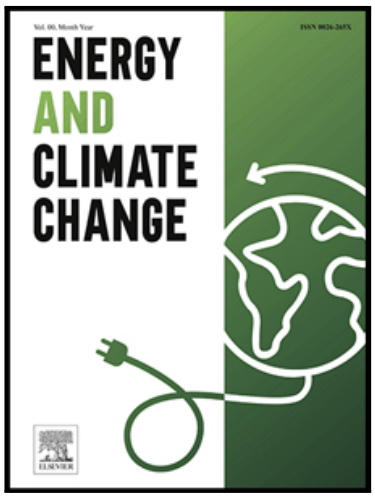

Quantifying and monitoring multiple impacts resulting from the implementation of a fair energy transition in coal regions across the European Union

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Highlights:

- Definition of fair energy transition
- Index quantifying impacts from implementation of fair energy transition
- Impacts from social, economic, environmental, and technical dimensions
- Tool for policy makers implementing energy transition

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Quantifying and monitoring multiple impacts resulting from the implementation of a fair energy transition in coal regions across the European Union

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Abstract

Coal regions are particularly vulnerable to the negative impacts that can arise due to the green energy transition. These impacts can be social, economic, environmental, or technical. A fair energy transition ensures that all the impacts arising from different dimensions are considered and treated evenly. Each coal region in the European Union has specific characteristics. Therefore, and index was developed utilising a Multi-Criteria Decision Analysis (MCDA) methodology to understand and to quantify the degree to which impacts related to a fair energy transition change over time and affect coal regions across the European Union. The index was adapted to perform country-level, dimensional, and regional analyses. The ex-post analyses investigated the evolvement of all impacts from a baseline period to a new timeline, illustrating areas for potential policy intervention per region. Ultimately, this can help to identify appropriate policies and measures, thereby facilitating the implementation of a truly fair energy transition across coal regions.

Key words: Fair Energy Transition, multiple impacts, coal regions, EU, MCDA

Word Count: 7,951

List of abbreviations: Just Transition Fund (JTF); Just Transition Mechanism (JTM); European Commission (EC), European Union (EU); Nomenclature of Territorial Units for Statistics (NUTS); Multi-Criteria Decision-Making (MCDA); Multi-Criteria Analysis (MCA); European Green Deal (EGD); Member State (MS); Fair Energy Transition Index (FETI); Simple Additive Weighting (SAW); Sustainable Development Goal (SDG); United Nations (UN); Sustainable Energy and Climate Action Plan (SECAP)

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1. Introduction

The European Union (EU) with its European Green Deal (EGD) has set an objective to become the first climate-neutral continent by 2050. In doing so, it aims to "transform the EU into a fair and prosperous society" (p. 2), preserving and enhancing its economic capacity, and at the same time shielding its citizens from environmental hazards; whilst ensuring that the transition is just [1]. To achieve these goals, the EU set up a dedicated fund, called the Just Transition Fund (JTF), as part of the larger Just Transition Mechanism (JTM), aimed at "leaving no one behind" (p. 2) [1]. While it is strongly emphasised that there is a need to ensure that this transition happens in a just and fair way, it is also

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recognised that not all Member States (MS) have the same starting point or equal capacities [2]. In fact, not even regions within one MS present the same starting conditions to implement the energy transition, due to the uneven distribution of resources and differing socioeconomic conditions [3]. Additionally, while the political, legislative, and moral willingness to promote an energy transition that is fair and just is evident throughout various EU legislations, recommendations, and policy packages; there is no clear definition of what exactly constitutes a fair and just transition, beyond the principle of *leaving no one behind*. These two terms can be found in many such documents, but they tend to be used interchangeably [4].

The main research objective of this paper is to delineate an index for quantifying, monitoring, and evaluating the multiple impacts resulting from the implementation of a fair energy transition in coal regions across the EU. In fact, the quantification and evaluation of how fair energy transitions are being implemented has been found to be a knowledge gap in the literature [5]. This paper builds on the findings of Peretto et al. when assessing territorial just transition plans in coal regions [6]; starting from the previously found impacts and expanding and updating these to develop a more comprehensive quantitative index. The delineated fair energy transition index (FETI) will allow to accurately rank all EU coal regions in correspondence to the degree to which the energy transition is being implemented in a fair way. By doing so, not only will it be possible to monitor the implementation of a fair energy transition in specific coal regions, but also to highlight major areas of intervention per region. The following will be done by applying a Multi-Criteria Decision Analysis (MCDA) approach, considering quantitative elements. The main research objective leads to two main research questions: *i) How can we quantify and monitor impacts resulting from the implementation of a fair energy transition in coal regions across the EU? ii) Which impacts resulting from the implementation of a fair energy transition need to be considered in order to quantify and monitor the latter?*

Throughout the literature, the term “just energy transition” is more utilised than “fair energy transition”. In fact, when performing a search query on Scopus with the words “just energy transition" this yielded 355 results. On the other hand, when searching for “fair energy transition”, this yielded only 20 results, with no definition of fair energy transition being found in the literature. While conceptual differences between a just and fair transition exist in the literature, they are not major. In fact, a just transition is often portrayed as a global transition, considering humanity as a whole when talking about post-carbon societies [7]. On the other hand, a fair energy transition can be more temporally and spatially focused, as long as it considers principles of fairness and justice and focuses on the most vulnerable [5].

Closely related to ensuring a fair energy transition is the concept of vulnerability and understanding which groups of people are more vulnerable to the transition. In general, vulnerability can describe the “propensity or predisposition to be adversely affected”, often referring to the potential negative impact of a specific external factor or change [8]. To understand which groups are especially at risk of being vulnerable, three interrelated dimensions can be used: (i) exposure, (ii) sensitivity and (iii) adaptive capacity [9]; [10]; [11]. Following the definitions of Adger, exposure can be understood as “the nature and degree to which a system experiences environmental or socio-political stress”; sensitivity as “the degree to which a system is modified or affected by perturbations”; and adaptive capacity as “the ability of a system to evolve in order to accommodate environmental hazards or policy change and to expand the range of variability with which it can cope” (p. 270) [9]. Understandings of vulnerability based on this conceptualisation have been used, for instance, in the context of energy policy at the community level [11] or to understand fuel poverty affecting households [12].

The energy transition can be understood as a multifaceted, multi-domain, and long-term process entailing impacts stemming from economic, environmental and social dimensions [18]; [19]. These

dimensions have been utilised extensively in the literature [20]; [21]; [22] in addition to being defined by the European Commission (EC) when considering fair transitions [2]. These three dimensions allow to provide a broader welfare analysis of a given country, or in this case region, instead of focusing on purely economic factors (e.g., Gross Domestic Product (GDP)) [18]. Additionally, Merzić et al. [17] stress the importance of considering also technical capacities, funding, and institutional support when considering energy transitions in coal regions specifically. In fact, coal regions are inevitably more vulnerable to suffering the negative impacts of the energy transition [2], being these regions highly economically dependent on fossil fuels and thus inevitably bearing a greater share of the burdens of the transition, with 6% of all EU regions being classified at high risk [19]. Following the previously mentioned definition of vulnerability, these regions present high exposure, high sensitivity and potentially low adaptive capacity, making these vulnerable to the energy transition.

Hereby, a fair energy transition will be defined as a multifaceted and long-term process entailing a series of impacts stemming from different dimensions which will affect society more or less adversely based on its vulnerability to the energy transition, while aiming to ensure that all impacts are treated evenly, as to provide a transition that is fair, prioritising people's welfare over regional economic interest. Hence, this definition considers a fair energy transition as one that enhances the overall welfare of the region by improving all impacts rather than focusing on only one. This means that performing excellently on one or two specific impacts will not result in implementing the energy transition in a fair way. In this paper, the context will be geographically bounded to the regional level. In addition, the scope of the research will be focused on EU coal regions, being these specifically highly vulnerable to the energy transition.

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2. Methodology and Data Selection

2.1. Geographical scope

Coal regions are particularly vulnerable to the negative impacts which will follow from the implementation of a fair energy transition. As previously mentioned, these regions present high exposure, high sensitivity and potentially low adaptive capacity. This means that the impacts stemming from the transition will not only differ by country, but also by region within the same country. The different impacts will differ mainly based on the coal and energy intensity of the region, but also on its general economic performance, labour market, employment levels, and sector specialisation [19].

Ensuring that the transition within EU coal regions is fairly implemented is paramount to prevent some regions from benefitting economically, while others remain stuck in a stagnant regional economy leading to negative socioeconomic consequences. More specifically, all EU coal regions which applied to the JTF will be considered, meaning a total of 29 coal regions from 12 different countries. This was chosen as to ensure that all considered regions had access to the same type of funding, ensuring a financial baseline from which to start the analysis. These are summarised in Table 1. The Nomenclature of Territorial Units for Statistics (NUTS) is a nomenclature of the EC used by Eurostat. The latter divides countries in regions (NUTS2) and regional units (NUTS3) [22].

Table 1: List of EU coal regions that applied to the JTF [23].

Country	Region	NUTS2 code
Bulgaria	Southeastern Bulgaria	BG34
	Southwestern Bulgaria	BG41
Croatia	Adriatic Croatia	HR03
Czechia	Northwestern Czechia	CZ04
	Moravia-Silesia	CZ08
Germany	Brandenburg	DE40
	Düsseldorf	DEA1
	Köln	DEA2
	Münster	DEA3
	Dresden	DED2
	Leipzig	DED5
	Saxony-Anhalt	DEE0
Greece	Western Macedonia	EL63
	Peloponnese	EL65
Hungary	Northern Hungary	HU31
Italy	Sardinia	ITG2
Poland	Lesser Poland	PL21
	Silesia	PL22
	Greater Poland	PL41
	Lower Silesia	PL51
	Łódzkie	PL71
	Lublin	PL81
Romania	Southwestern Oltenia	RO41
	Macro Region 4 West	RO42
Slovakia	Western Slovakia	SK02
Slovenia	Eastern Slovenia	SI03
Spain	Principality of Asturias	ES12
	Aragón	ES41
	Castilla y León	ES24

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2.2. Methodology

The research follows four main steps: i) review, update, and adapt the impacts and indicators related to the implementation of just transitions in coal regions found in Peretto et al. [6]; ii) collect data and create a baseline; iii) develop an index as to quantitatively assess how the impacts related to the implementation of fair transitions is impacting coal regions; iv) apply the index to all EU coal regions that adhered to the JTF and rank these accordingly.

First, the impact and indicator matrices developed in Peretto et al. [6] serve as a starting point. These matrices were developed specifically to assess the implementation of just transitions in coal regions. These matrices are based on a thorough literature review of impacts and related indicators to quantify these. A non-weighted multi-criteria analysis (MCA) was performed to delineate these matrices, justifying the need for an indicator approach [6]. The list of impacts was updated and expanded to better reflect the concept of a fair transition. The impact matrix includes several impacts that are available only qualitatively, as no related indicator to quantify such impacts was found [6]. Such impacts were excluded in this case. In fact, the developed index only considers quantifiable impacts. Additionally, the demographic dimension was not considered in this case, as only one of the two impacts was quantifiable [6]. It was instead decided to include a technical dimension, as suggested by Merzić et al. [17]. Lastly, to develop the index a weighted MCDA was performed, as opposed to the

non-weighted MCA performed in Peretto et al. [6]. This means that the present index is fully quantitative, making it more reliable and more suited to the context of coal regions; even though some qualitative impacts related to the implementation of fair transitions might not be included. Additionally, some proxy indicators might not fully capture the social fairness and equity. Nonetheless, proxy indicators are useful to compensate for the lack of data [24], [25].

Second, the FETI was developed to provide a time-bounded ex-post analysis of how impacts resulting from fair energy transitions changed. The index enables to track the regions (and countries) evolvement of impacts over time. In fact, the authors acknowledge that positive (or negative) evolvements of impacts over time might be caused by national reforms for example rather than purely fair transition actions. Nonetheless, the FETI allows to understand how certain impacts have been evolving, and which ones have been evolving better (or worse) than others across different dimensions. This facilitates both regional monitoring and comparative evaluation across EU coal regions, identifying key areas that require intervention.

The developed index is constructed by considering different indicators quantifying different impacts. Various applications and methodologies stemming from MCDA are available in the literature, with varying differences based on the problem being considered, the evaluation criteria being employed, and the type of data being utilised [26]. Among various MCDA approaches, the study adopts the methodology from SYNERGISE+, an existing sustainability decision-making tool [27]. SYNERGISE+ follows the general MCDA model proposed by Wątróbski et al. [26], stemming from an analysis of 56 MCDA methods (including AHP, TOPSIS, and PROMETHEE among others), which consists of eight sequential steps (Figure 1). Essentially, starting from the problem definition, the MCDA process ends by ranking and evaluating the different considered candidates either singularly, either by grouping different candidates together, or ranking these according to different criteria. In this case, the candidates correspond to the considered coal regions.

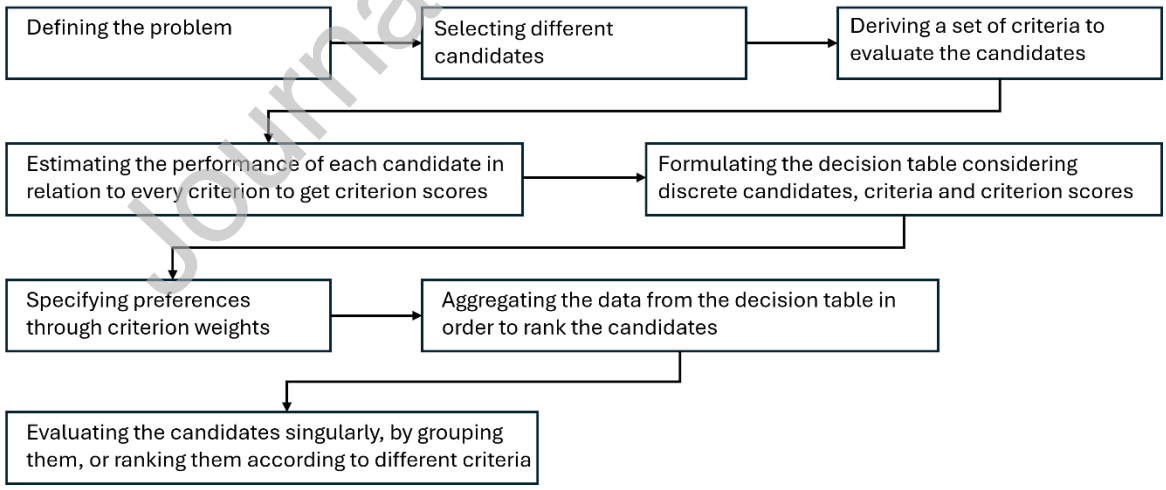

Figure 1: Summary of steps present in the delineation of a general MCDA framework.

2.2.1. Adaptation of SYNERGISE+ to the fair energy transition

Hereby, the SYNERGISE+ MCDA methodology [27] will be employed to develop the FETI. Whereas originally developed in the context of Sustainable Energy and Climate Action Plans (SECAPs), including

both adaptation and mitigation actions as part of the same decision-making process; SYNERGISE+'s logic remains applicable to fair energy transitions as well. In fact, the developed framework ranks the performance of each region considering every individual indicator and thereafter ranks the performance of each region for every indicator (i.e., criterion), impact, and dimension. Additionally, the performance of different regions can also be considered together to thereafter illustrate the performance of every country. The resulting methodology is summarised in Figure 2.

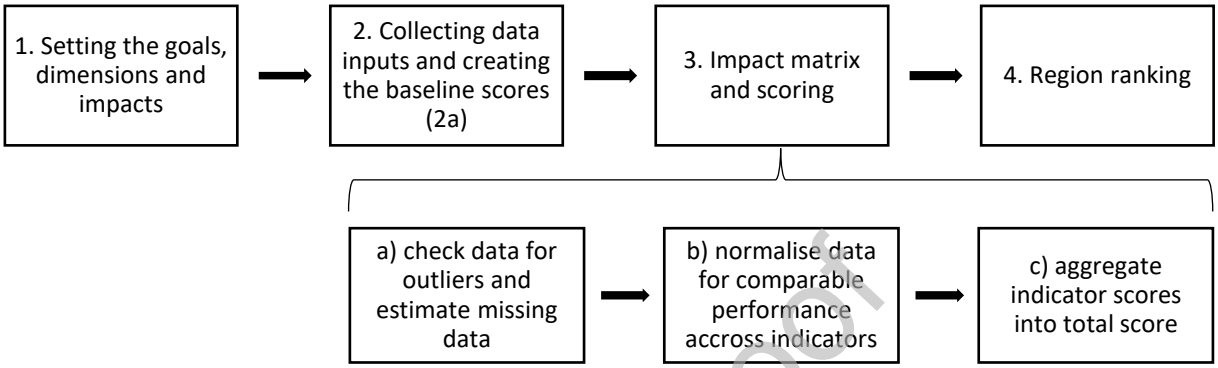

Figure 2: Index methodology.

The matrix score is determined using the Simple Additive Weighting (SAW) method, which involves summing the products of each score and its corresponding criterion weight. For data normalisation, min-max normalisation was used, as one of the recommended methods by Vafaei et al. [28]. Notably, the combination of max linear normalisation with SAW has been found to yield the most consistent results and remains the most robust against variations in criterion weights [29]. Although max linear normalisation was considered, it failed to adequately account for countries experiencing regression in certain indicators, thereby limiting its suitability. Given these limitations, min-max normalisation was selected as the most appropriate approach for this study, ensuring a balanced representation of regional disparities while maintaining methodological robustness.

Similar applications were found in the literature. Yanguas Parra [30] delineated an indicator considering regions where more than 70% of national coal production is focused, however considering the 10 largest coal producing countries; thus taking a global view of the issue. On the other hand, Vrontisi et al. [19] outlined a socioeconomic risk indicator to delineate the most vulnerable EU regions to the transition; hence focusing on highlighting which regions were most at risk rather than assuming that these regions were already at risk and thereafter assessing the degree of implementation of a fair transition. Additionally, Chlechowitz et al. [31] developed a multi-criteria indicator consisting of 13 criteria to capture the different impacts related to the application of the Energy Efficiency First Principle; whereas Reuter et al. [32] outlined a composite indicator to measure the multiple benefits of energy efficiency consisting of 20 different indicators. Lastly, the Handbook on constructing composite indicators developed by the OECD and Joint Research Centre (JRC) was considered as a best practice [33].

2.2.2. Summary and temporal scope

To summarise, the FETI quantifies different impacts stemming from the implementation of a fair energy transition in EU coal regions. It illustrates how each region performs across different impacts thereby identifying critical areas for policy intervention. The current application of the index is limited to an ex-post analysis, assessing the status quo prior to the implementation of the JTF. However, the selection

of temporally comparable indicators and the structure of the index enable its future use as a monitoring tool [34]. Once sufficient longitudinal data becomes available, the index could support ex-post trend analyses and potentially be adapted for ex-ante assessments to guide policy prioritisation.

Currently, data is available only until the year 2022. Considering that the JTF regulation came into force in 2021 [2], not enough data would be available to assess how the implementation of the fund changed and affected the regions. Nonetheless, it must be noted that all EU countries (except Poland) have already established official coal phase-out plans, which means that transformation processes in coal regions were already underway [35]. However, such transformation processes were not necessarily implemented by applying the "leave no one behind" principle but were rather triggered by the willingness to reduce local emissions, by cheaper coal imports or by substitution with cleaner fuels, varying from country to country. Hence, whereas such processes were already present before the implementation of the JTF, the latter further greatly incentivised such processes and clearly delineated the need to apply these transformation processes in a fair way. Therefore, to assess the status quo and performance of the regions before the implementation of the JTF, a timeline of five years was chosen from 2016-2020, as to already highlight to which areas should the fund be directed per region (and country), but also in general throughout the EU. Ideally, this baseline should be evaluated against a new five-year average dataset from 2021 to 2025 to establish a regional trend in change over time. Given the data availability constraint, a single-year comparison (2022 vs. baseline) was selected as the most accurate approach. Using earlier years for comparison could misrepresent actual changes, as it would incorporate pandemic-related anomalies from 2020 and 2021, which may not be reflective of 2022 or future trends.

2.3. Data Selection

While various reputable statistical repositories were considered, the decision to focus exclusively on Eurostat as the primary data source for this study was guided by practical considerations. Eurostat provides a harmonised and standardised dataset covering all EU MS, ensuring consistency in data collection methodologies and allowing for reliable cross-country comparisons and replicability [24]. Given the objective of this study to assess the fair energy transition across coal regions in the EU, maintaining data uniformity is critical to ensure that the derived insights remain comparable across different regions. Additionally, Eurostat data is continuously updated and aligned with official EC policies, making it one of the most authoritative sources for socio-economic, environmental, and energy-related statistics. The availability of long-term time series data from Eurostat further enhances its suitability for tracking trends over time, a key aspect in assessing the impacts of the energy transition.

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3. Results

3.1. Step 1: Derivation of impacts to evaluate the implementation of a fair energy transition in coal regions

A review of impacts stemming from the implementation of a fair energy transition in coal regions was performed. For every found impact, related indicators were delineated in order to quantify all selected impacts. A total of 11 impacts and 22 indicators were selected. These are summarised in Table 2. In

Peretto et al. [6], 18 impacts and only 12 indicators were chosen. For the rationale of selecting those indicators to describe the related impacts, see [6]. Such difference can be explained by the employment of MCDA in opposition to non-weighted MCA [6]. In fact, to apply MCDA and thus weight each impact, only quantifiable impacts will be considered; meaning that at least one indicator per impact will be selected. In total, 5 impacts and 9 indicators were taken from Peretto et al. [6]; the rest were added following literature review. Hence, the indicators are grounded in empirical literature, with the references available in Table 2. Table 3 illustrates the full information about data sources.

It can be noticed that two thirds of the indicators are available only at national level. Lack of localised bottom-up data has been recognised as a vital issue, hindering impact assessments across MS, caused also by the disconnection between academia and researchers and local practitioners and policymakers [24]. Whereas this lowers the accuracy of estimating the exact effect at regional level, it enables the index to provide ranking at national level, by grouping regions from the same country together. This can be particularly useful especially when considering the environmental and technical dimension, as all indicators are available exclusively at national level.

*Table 2: Summary of all impacts and associated indicators considered. *Data unavailable for Silesia and Western Macedonia; while for German regions only national data was available.*

Impact	Indicator	Data granularity available	Justification for selection	Literature reference
Social Dimension				
Female unemployment	Female unemployment rate	NUTS2	Quantifies the female unemployment	[6]
Affordable energy	Inability to keep home adequately warm	National	Quantifies how many households cannot afford to adequately heat	[6]
	Arrears on utility bills	National		[6]
Living conditions	Overcrowding depending on type of dwelling	National	Signals suboptimal living conditions	Eurostat
	Severe housing deprivation rate	National		[37]
	Population change	NUTS2	People moving to or leaving the region signals whether the region offers inviting living conditions	[38]
	Share of buses and trains inland passenger	National	Transport (un-) availability greatly influences the daily lives of citizens in a region	Eurostat
Poverty alleviation	Severe material and social deprivation rate	NUTS2*	These indicators not	[6]

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	People living in households with very low work intensity	NUTS2*	only describe general poverty but also energy poverty	[6]
	Risk of poverty and social exclusion rate	NUTS2		[6]
Health and well-being	Self-reported unmet need for medical examination	National	These indicators quantify how the health and well-being of residents is perceived	[37]
	Self-perceived health	National		Eurostat
Economic Dimension				
Employment	Unemployment rate	NUTS2	Quantifies unemployment	[6]
	Young people neither in employment nor education nor training (NEET)	NUTS2	Quantifies unemployment within younger people	[37]
Economic growth	Real growth of regional GDP per year	NUTS2	Quantifies the economic performance of the region	[38]
Environmental Dimension				
Resource efficiency	Energy intensity of GDP	National	Quantifies the environmental impact caused by general energy usage. Carbon, GHG, or methane intensity of GDP would be more accurate, however not present on Eurostat	[6]
	Share of energy from renewable sources	National	Quantifies what is being done to lower the environmental impact of energy	[6]
Risk and vulnerability to climate impacts	Net GHG from LULUCF	National	Quantifies the land emissions of GHG	Eurostat
	Climate related economic losses	National	Quantifies the degree to which climate (and the environment) impacts the region	Eurostat
Technical Dimension				
Structural changes in related industries	Air emission from industry	National	Technical structural	Eurostat

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			changes result in more efficient industries, lowering the emissions of particulates <2.5 µm	
Innovation	R&D personnel by sector	National	The growth in the number of personnel and investments in R&D quantifies innovation. No particular correlation between the two indicators was found	Eurostat
	GDP expenditure on R&D	National		Eurostat

Table 3: Summary of all data information per indicator.

Indicator	Source	Time period	Sample code	Reliability checks	Assumptions
Female unemployment rate	Eurostat	2016-2020 & 2022	lfst_r_lfu3rt	Regular	None
Inability to keep home adequately warm	Eurostat	2016-2020 & 2022	ilc_mdes01	Regular	None
Arrears on utility bills	Eurostat	2016-2020 & 2022	ilc_mdes07	Regular	None
Overcrowding depending on type of dwelling	Eurostat	2016-2020 & 2022	ilc_lvho05d	Regular	Only for people living in rural areas
Severe housing deprivation rate	Eurostat	2016-2020 & 2022	sdg_11_11	Regular	None
Population change	Eurostat	2016-2020 & 2022	demo_r_gind3	Regular	None
Share of buses and trains inland passenger	Eurostat	2016-2020 & 2022	sdg_09_50	Regular	Sum of buses and trains considered
Severe material and social deprivation rate	Eurostat	2016-2020 & 2022	ilc_mdsd18	Regular	None
People living in households with very low work intensity	Eurostat	2016-2020 & 2022	ilc_lvhl21	Regular	None
Risk of poverty and social exclusion rate	Eurostat	2016-2020 & 2022	ilc_peps11n	Regular	None
Self-reported unmet need for medical examination	Eurostat	2016-2020 & 2022	sdg_03_60	Regular	None
Self-perceived health	Eurostat	2016-2020 & 2022	hlth_silc_02	Regular	Self-perceived bad or very bad health

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Unemployment rate	Eurostat	2016-2020 & 2022	lfst_r_lfu3rt	Regular	None
Young people neither in employment nor education nor training (NEET)	Eurostat	2016-2020 & 2022	edat_lfse_22	Regular	From 18 to 29 years if age
Real growth of regional GDP per year	Eurostat	2016-2020 & 2022	tgs00037	Regular	None
Energy intensity of GDP	Eurostat	2016-2020 & 2022	nrg_ind_ei	Regular	All data is in Purchasing Power Standard (PPS)
Share of energy from renewable sources	Eurostat	2016-2020 & 2022	nrg_ind_ren	Regular	None
Net GHG from LULUCF	Eurostat	2016-2020 & 2022	sdg_13_21	Regular	None
Climate related economic losses	Eurostat	2016-2020 & 2022	sdg_13_40	Regular	None
Air emission from industry	Eurostat	2016-2020 & 2022	sdg_09_70	Regular	Considering only <PM2.5 particulates
R&D personnel by sector	Eurostat	2016-2020 & 2022	sdg_09_30	Regular	Considering only the business enterprise sector
GDP expenditure on R&D	Eurostat	2016-2020 & 2022	sdg_09_10	Regular	Considering only the business enterprise sector

3.2. Step 2: Collecting the data and creating the baseline

An average of Eurostat data from 2016 to 2020 was calculated for each indicator and region, providing a stable baseline period that captures medium-term trends prior to the implementation of the JTF. Based on the five-year regional averages, the minimum and maximum values across all considered regions were determined through a combined process of statistical observation and expert judgement. In cases where extreme outliers were identified – values that deviated substantially from the broader distribution – these were excluded to avoid distortions in the normalisation process. The resulting minimum and maximum values were then used as reference points for normalising data from subsequent years across all regions. For example, when considering *female unemployment*, Western Macedonia presented the worst value (33.8%) while Münster presented the best value (2.9%). These two values were thus taken as the maximum and minimum values for the baseline for the impact of female unemployment across all regions. The maximum and minimum values per indicator can be found in Table 4.

Following this, max-min normalisation was applied, standardising all baseline-period values within a 0 to 1 range. The baseline values are the same for all countries, as to have a European level analysis. Following the previous example considering female unemployment, Western Macedonia would thus have a value of 0, while Münster a value of 1, and all other regions a baseline value in between. This also allows to have both absolute and relative understandings of improvements/declines. For example,

considering again female unemployment, one can see that Western Macedonia has a much lower value than Münster, hence hinting that this is an impact that needs to be adequately addressed. Nonetheless, when comparing the baseline value and the 2022 value for Western Macedonia, one will see that indeed an improvement has happened in the region. Additionally, such normalisation process - considering the values for all regions - allows to put realistic boundaries, rather than theoretical ones (e.g., trying to estimate the "best value" for female unemployment). It is important to note that data points from post-baseline years may exceed the established maximum; in such cases, the resulting normalised values can surpass 1. In this framework, a region scoring 1.5 in a subsequent assessment would indicate that it has surpassed the previous best performance by 50% in that category. This normalisation method enables both relative and absolute assessments of progress, allowing policymakers to track improvements or setbacks in each dimension over time. To summarise, the regional values per indicator per year were normalised with the max-min method, considering all 29 regions, within a range from 0 to 1.

*Table 4: Baseline values for indicator normalisation (2016–2020): units, best, worst and average observed performance across all considered coal regions. *1 when normalised. **0 when normalised*

Indicator	Unit	Best value*	Worst value**	Average
Female unemployment rate	Percentage of population in the labour force	2.9	33.8	7.6
Inability to keep home adequately warm	Percentage	2.9	33.4	9.0
Arrears on utility bills	Percentage	2.2	35.4	10.5
Overcrowding depending on type of dwelling	Percentage	4.2	46.8	22.5
Severe housing deprivation rate	Percentage	1.9	16.3	5.9
Population change	Percentage	9.5	-48.1	-2.9
Share of buses and trains inland passenger	Percentage	27.4	12.8	17.5
Severe material and social deprivation rate	Percentage	2.6	31.5	8.7
People living in households with very low work intensity	Percentage	3.2	19.7	8.9
Risk of poverty and social exclusion rate	Percentage	11.7	47.0	22.9
Self-reported unmet need for medical examination	Percentage	0.2	9.3	2.4
Self-perceived health	Percentage	6.8	17.1	10.1
Unemployment rate	Percentage	2.9	26.3	7.1
Young people neither in employment nor education nor training (NEET)	Percentage from 18-29 years of age	8.2	35.6	17.2
Real growth of regional GDP per year	Percentage change on previous year	4.7	-5.5	0.9
Energy intensity of GDP	Kg of oil equivalent per thousand euro in PPS	86.1	171.7	118.1
Share of energy from renewable sources	Percentage	28.6	13.4	17.5
Net GHG from LULUCF	Tonnes per capita	-2.5	0.1	-0.7
Climate related economic losses	Euro per inhabitant	0.18	97.0	33.0
Air emission from industry	Grams of particulates <2.5 µm per euro, chain linked volume (2010).	0.02	0.3	0.1

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R&D personnel by sector	Percentage of population in the labour force	1.1	0.1	0.6
GDP expenditure on R&D	Percentage of GDP	2.1	0.3	1.1

To assess potential redundancy and validate the multidimensionality of the selected indicators, a covariance analysis was performed on the normalised baseline data (2016–2020). The covariance matrix reveals the strength and direction of linear relationships between pairs of indicators. While some moderate positive and negative covariances were observed—particularly among social and economic indicators—most values remained within acceptable thresholds, indicating low multicollinearity. This supports the internal consistency of the index framework and confirms that each indicator contributes unique information to the overall assessment.

3.3. Step 3: Impact matrix and scoring

The weighting structure is organised into three hierarchical levels and is detailed in Table 5. At the first level, four broad impact dimensions are considered: social, economic, environmental, and technical. The second level consists of 11 impacts, which are distributed across these four dimensions. The third level comprises 22 indicators, each representing a measurable component of the respective impacts (Table 2). The weight allocation follows a bottom-up approach, ensuring a relatively balanced distribution of weights across the second-level impacts. This is in line with the considered definition of fair energy transition, "aiming to ensure that all impacts are treated evenly", defined in the introduction. Additionally, it was found that the weighting processes (and the selection) related to such indicator application mostly relied on opinions of authors [39]. This is understandable, particularly for fair energy transitions as this is a rather new topic, with indices differing depending on the intended application. For example for energy poverty, another multidimensional phenomenon related to the energy transition, no protocol for weighting contributions is available [40], although machine learning has been employed to solve such knowledge gap [41].

The considered indicators present differing levels of data availability. In fact, the social and economic dimensions are primarily based on regional (NUTS2) indicators, which provide a more localised representation of fair transition impacts, whereas the environmental and technical dimensions rely mostly on national-level indicators, which lack the same level of regional specificity. The importance of including the environmental dimension in such analyses was stressed in [39]. The regional production and consumption in the energy mix of renewables is an accurate indicator, also to quantify the fact that households cannot use better heating options as these are simply not available [42]. Such indicator is however only available at national level. The same can be said for all the other environmental and technical impacts. Nonetheless, it was decided to still consider the two dimensions as these are crucial in quantifying impacts of a fair energy transition. To account for this, slightly higher absolute weights were assigned to the social and economic impacts (10%), as opposed to technical and environmental impacts (7.5%). This deviates slightly from the given definition of fair energy transition but allows to still consider the two dimensions. As a result, the social dimension was assigned the highest weight at 50%, reflecting the social nature of the index and the fact that it encompasses five distinct impacts, in contrast to only two impacts in each of the other dimensions. The economic dimension was allocated 20%, while the environmental and technical dimensions were each assigned 15% (Table 5).

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*Table 5: Weight distribution of all three levels (dimension/impact/indicator). *Impact absolute weight is calculated by multiplying the impact relative weight with dimension weight.*

Impact	Impact relative weight (A)	Impact absolute weight (B)*	Indicator	Indicator relative weight (C)	Indicator absolute weight = B * C
Social dimension (50%)					
Female unemployment	20%	10%	Female unemployment rate	100%	10%
Affordable energy	20%	10%	Inability to keep home adequately warm	50%	5.0%
			Arrears on utility bills	50%	5.0%
Living conditions	20%	10%	Overcrowding depending on type of dwelling	13.33%	1.3%
			Severe housing deprivation rate	13.33%	1.3%
			Population change	60%	6.0%
			Share of buses and trains inland passenger	13.33%	1.3%
Poverty alleviation	20%	10%	Severe material and social deprivation rate	33%	3.3%
			People living in households with very low work intensity	33%	3.3%
			Risk of poverty and social exclusion rate	33%	3.3%
Health and well-being	20%	10%	Self-reported unmet need for medical examination	50%	5.0%
			Self-perceived health	50%	5.0%
Economic Dimension (20%)					
Employment	50%	10%	Unemployment rate	70%	7.0%
			Young people neither in employment nor education nor training (NEET)	30%	3.0%
Economic growth	50%	10%	Real growth of regional GDP per year	100%	10.0%
Environmental Dimension (15%)					
Emissions reduction and resource efficiency	50%	7.5%	Energy intensity of GDP	30%	2.3%
			Share of energy from renewable sources	70%	5.3%
Risk and vulnerability to climate impacts	50%	7.5%	Net GHG from LULUCF	70%	5.3%
			Climate related economic losses	30%	2.3%
Technical Dimension (15%)					
Structural changes in related industries	50%	7.5%	Air emission from industry	100%	7.5%
Innovation	50%	7.5%	R&D personnel by sector	50%	3.8%
			GDP expenditure on R&D	50%	3.8%

Such division was corroborated by a sensitivity analysis. Seven distinct weighting scenarios were considered (Table 6). Each scenario applied a different set of weights to the 11 criteria representing the social, economic, environmental, and technical dimensions of the transition. These included scenarios with equal weights per dimension, equal weights per criteria, and dominance-based scenarios emphasizing specific dimensions such as economic, environmental, or social.

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The **Equal weights per dimension** scenario assigns 25% weight to each of the four dimensions ensuring an arithmetically balanced approach. However, this scenario can lead to unbalanced outcomes at the indicator level, as dimensions with fewer indicators receive disproportionately higher weights per criterion. The **Equal weights per criterion** scenario addresses this by giving equal weight to each indicator, which results in a 45% overall weight for the social dimension due to its larger number of criteria. This approach ensures equal importance across all indicators while emphasising social aspects. The **Economic-, Environment- and the Technical-dominant scenario**, which assigns 45% of the total weight to the main dimension and 18% to others, are unbalanced and risk overlooking critical social dimensions. Such scenarios that prioritize dimensions other than the social one tend to produce unbalanced outcomes due to the disproportional distribution of criteria across dimensions. The social dimension comprises the largest number of criteria in the index; thus, when it is assigned a lower overall weight, each individual social criterion receives a significantly smaller share compared to criteria in more narrowly defined dimensions (e.g., environmental or technical). This skews the results in favour of dimensions with fewer but more heavily weighted criteria, potentially undermining the relevance of social impacts in a socially focused transition framework. **Extreme social scenario** was also tested, assigning 82% of the weight to the social dimension and only 6% to each of the others. While it maximizes the emphasis on social fairness, it undermines the multi-impact character of a just transition.

Finally, the **Chosen scenario** was selected to reflect the normative emphasis of a fair energy transition, in line with EU policy principles. It is very similar to the equal weights per criterion scenario and allocates 50% to social, 20% to economic, and 15% each to environmental and technical dimensions. This configuration ensures that the plurality of social criteria is adequately represented, while still capturing the importance of economic stability, environmental sustainability, and technical innovation. It balances the need for social equity with the multidimensional nature of transition planning, offering a fair yet pragmatically weighted framework. Hypothetical regional performance scores were calculated under each scenario. This allowed for evaluating how regional rankings shift in response to alternative policy weightings, thereby validating the model's flexibility and its alignment with different policy goals. These are included in the annex.

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Table 6: Weights under six different weighting scenarios.

		Criteria final weight											
Weighting Scenario	**Summary Implication**	**Female Unemployment**	**Affordable Energy**	**Living Conditions**	**Poverty Alleviation**	**Health & Well-being**	**Employment**	**Economic Growth**	**Emission Reduction & RE**	**Climate Vulnerability**	**Structural Change**	**Innovation**	**Total**
Equal weights per dimension	Equal dimensional importance, but may underrepresent domains with fewer criteria	0.05	0.05	0.05	0.05	0.05	0.13	0.13	0.13	0.13	0.13	0.13	1
Equal weights per criterion	Balanced, reflecting social dominance via more criteria	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	1
Economic-dominant	Prioritizes economic impact and growth	0.04	0.04	0.04	0.04	0.04	0.23	0.23	0.09	0.09	0.09	0.09	1
Environmental-dominant	Emphasizes green transition priorities	0.04	0.04	0.04	0.04	0.04	0.08	0.08	0.25	0.25	0.08	0.08	1
Technical-dominant	Focuses on innovation and industry structure	0.04	0.04	0.04	0.04	0.04	0.08	0.08	0.08	0.08	0.25	0.25	1
Extreme social	Social dimension dominates (82% of total weight)	0.16	0.16	0.16	0.16	0.16	0.03	0.03	0.03	0.03	0.03	0.03	1
Chosen scenario	Pragmatic social emphasis (50%), balanced with economic (20%), environm. and technical (7.5%)	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.08**	**0.08**	**0.08**	**0.08**	**1**

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To consider both academic rigor but also data granularity, three different analyses were performed. In fact, the previously described composition of FETI, corroborated by the sensitivity analysis, was utilised to perform a country-level, in which results from all coal regions within the same country are averaged to provide a single national score thus enabling cross-country comparisons; and a dimensional analysis, assessing performance across the four dimensions separately to highlight strengths and weaknesses within each thematic area. In fact, at national level, all the impacts remain valid. Nonetheless, to account for data granularity and to perform an accurate regional analysis of impact changes, a second application of the FETI was performed considering only the social and economic impacts. This way, 8/15 (53%) of indicators are at NUTS2 level. This allows to have a more precise analysis at regional level. To remain consistent with the definition of fair energy transition, the same weight was given to all impacts. This results in the social dimension having 70% of the weight and the economic one having 30%, as can be seen in Table 7.

*Table 7: Weight distribution of all three levels (dimension/impact/indicator) for the two-dimensional analysis. *Impact absolute weight is calculated by multiplying the impact relative weight with dimension weight.*

Impact	Impact relative weight (A)	Impact absolute weight (B)*	Indicator	Indicator relative weight (C)	Indicator absolute weight = B * C
Social dimension (70%)					
Female unemployment	20%	14%	Female unemployment rate	100%	14%
Affordable energy	20%	14%	Inability to keep home adequately warm	50%	7.0%
			Arrears on utility bills	50%	7.0%
Living conditions	20%	14%	Overcrowding depending on type of dwelling	13.33%	1.9%
			Severe housing deprivation rate	13.33%	1.9%
			Population change	60%	8.4%
			Share of buses and trains inland passenger	13.33%	1.9%
Poverty alleviation	20%	14%	Severe material and social deprivation rate	33%	4.6%
			People living in households with very low work intensity	33%	4.6%
			Risk of poverty and social exclusion rate	33%	4.6%
Health and well-being	20%	14%	Self-reported unmet need for medical examination	50%	7.0%
			Self-perceived health	50%	7.0%
Economic Dimension (30%)					
Employment	50%	15%	Unemployment rate	70%	10.5%
			Young people neither in employment nor education nor training (NEET)	30%	4.5%
Economic growth	50%	15%	Real growth of regional GDP per year	100%	15.0%

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3.4. Step 4: Application of the index and analysis

3.4.1. Country – level aggregation of coal regions

When looking at the average result of all coal regions per country, Germany was found to be the best performing country according to the baseline; however, this was not confirmed when considering the year 2022. In fact, Slovenia, Czechia, and Croatia performed just as well. This signals a positive improvement concerning the impacts of a fair energy transition. Nonetheless, it needs to be noted that only one Slovenian and one Croatian region were considered, namely Eastern Slovenia and Adriatic Croatia as opposed to the 7 German ones. In fact, since the scope of this research is limited to coal regions, when comparing countries, only the coal regions within the country need to be considered. Nonetheless, countries that present less coal regions, and thus countries where coal plays a smaller role at national level, will inevitably be skewed as they are being represented by only one or few regions. To obtain country-level values for countries presenting two or more regions, the average of the regional values was taken; thus, aggregating the regional values.

The largest positive improvement related to fair energy transition impacts was found in Croatia, followed by Greece. Nonetheless, the latter still presented the lowest levels for all impacts across all considered countries. This means that Greek coal regions are still impacted the most by the energy transition, with however some improvements not necessarily related to the actual implementation of fair energy transition policies. In the case of Croatia, it needs to be understood which dimensions presented the highest improvement, as to have a clearer understanding of which dimension/impacts caused such improvement and whether it was uniformly distributed. Czechia consistently ranked in the top three countries according to the index, with a constant and steady increase in its impact alleviation. On the other hand, Hungary presented the greatest decline, followed by Romania. Once again, it needs to be noted that only one Hungarian region was considered. Lastly, it can be concluded that whereas Bulgaria and Greece ranked the lowest in 2022, signs of improvement concerning the different impacts were found in Greek regions and, to a lesser extent, in Bulgarian ones. This hints to a possible implementation of dedicated policies, or general national improvement. Further analysis is needed to understand which impacts saw the greatest improvement, also to understand the degree to which these were *low hanging fruits*. Table 8 summarises the results.

Table 8: Summary of results for country-level aggregation of results.

Country	2016-2020 (Baseline) Dense Ranking	2016-2020 (Baseline) Index Value	2022 Index value	Net change	2022 Ranking
Germany	**1**	0.79	0.80	0.01	2
Slovenia	2	0.73	0.81	0.08	**1**
Czechia	3	0.72	0.81	0.09	**1**
Slovakia	4	0.69	0.71	0.02	4
Spain	5	0.65	0.68	0.03	5
Poland	5	0.65	0.78	0.13	3
Hungary	5	0.65	0.61	**-0.04**	7
Romania	6	0.63	0.63	-0.01	6
Croatia	7	0.60	0.81	**0.21**	**1**
Italy	8	0.56	0.63	0.07	6
Bulgaria	9	0.53	0.61	0.07	7
Greece	**10**	0.32	0.49	0.17	**8**

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3.4.2. Dimensional analysis

To have an accurate analysis at the dimensional level, the total achieved scores need to be related to the total achievable ones. This was calculated in the last line of Table 9. As can be seen, the environmental dimension achieved a score of only 0.06 out of a possible 0.15 in both the baseline and for 2022. Romania achieved a score of 0.13 in both timelines, whereas Italy and Hungary a score of only 0.01 for 2022. This is due to Italy performing very poorly in the "climate related economic losses" impact in 2022. On the other hand, Romania was the best performing country for this impact in both timelines. Nonetheless, such impact cannot be strictly related purely to the implementation of a fair energy transition, so caution needs to be taken when trying to relate such dimensional change causally to the fair energy transition implementation. Figure 3 provides more insights in how countries performed in the environmental dimension.

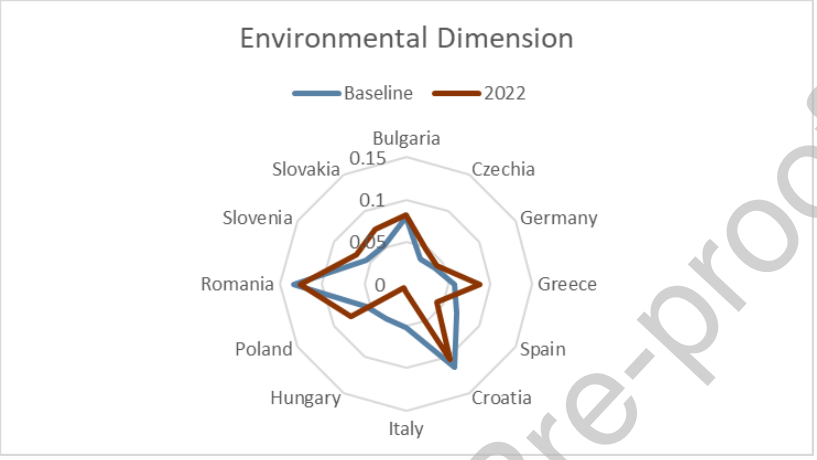

Figure 3: Country performance for the environmental dimension.

The social and economic dimensions presented the same scores for 2022. Nonetheless, by taking a closer look, one can see that the social dimension improved by 6% from the baseline to 2022 whereas the economic one improved by 10% (Table 9). The value that stands out in this case is the 0.25 achieved by Croatia in 2022 for the economic dimensions, 20% higher than the best possible achievable score (i.e., 0.2). Croatia performed very highly under the "economic growth" impact. This impact is quantified by utilising only one indicator, namely the "real growth of regional GDP per year" (Table 5). In the baseline, *Macro Region 4 West* presented the highest value (normalised to a value of 1); however, in 2022, *Adriatic Croatia* presented a value 65% higher than this one, hence obtaining the highest normalised value of 1.65. As *Adriatic Croatia* is the only coal region considered in Croatia, this explains the high performance of the country in the economic dimension. Additionally, the "economic growth" impact, together with the "female unemployment" impact, present the highest weights within the index (i.e., 10%) (Table 5). Regional economic growth alone cannot be causally attributed to the implementation of a fair energy transition; therefore, it can be concluded that this impact skewed the results to a certain degree. Figure 4 provides a greater overview for the two dimensions.

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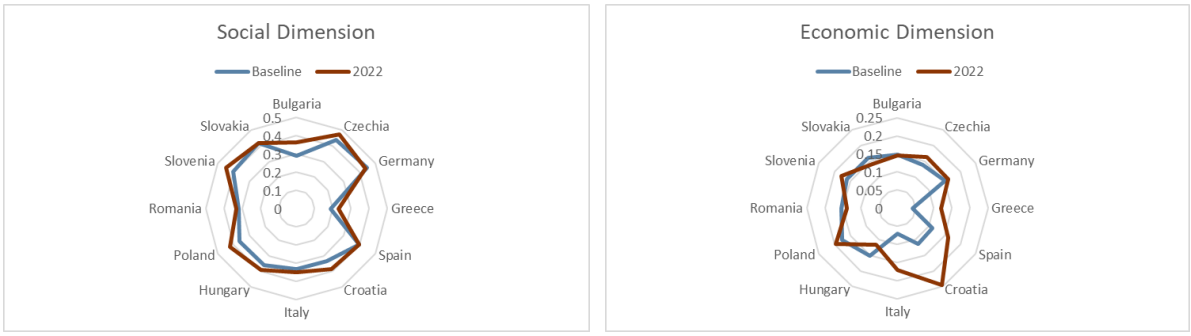

Figure 4: Overview of country performance in the social and economic dimensions.

The technical dimension did not present any surprising results. Germany achieved perfect scores in both timelines, resulting as having the best performing impacts from a technical perspective. Croatia presented the highest improvement, increasing from a value of 0.03 in the baseline to 0.07 in 2022 (Table 9). These impacts are at national level, and hence an improvement for such impacts cannot be causally related to the implementation of a fair energy transition. Nonetheless, considering such dimension provides a more holistic picture. Figure 5 provides a closer overview of the country performances for this dimension.

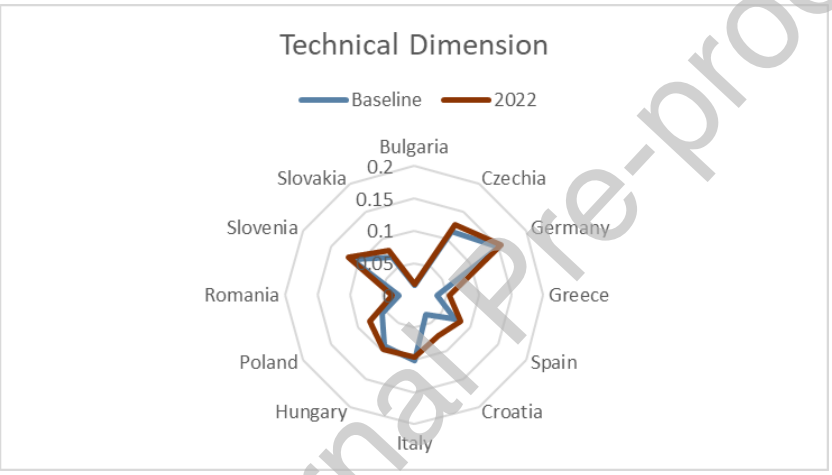

Figure 5: Country performance for the technical dimension.

By analysing the different dimensions, it became clear that more granular data will provide more accurate data, and that even though the environmental and technical impacts need to be considered, focusing on only the social and economic one will provide more accurate and robust results. In fact, the fair energy transition needs to be implemented at regional level, and in absence of more granular data, focusing on only two dimensions, social and economic, will allow for a more accurate analysis of how the impacts are affected at regional level.

Table 9: Summary of dimensional analysis results.

	Baseline 2016-2020				2022			
Country	Social	Economic	Environmental	Technical	Social	Economic	Environmental	Technical
Bulgaria	0.29	0.15	0.08	0.02	0.36	0.14	0.08	0.02
Croatia	0.33	0.11	0.11	0.03	0.38	**0.25**	0.10	0.07
Czechia	0.44	0.14	0.03	0.11	**0.47**	0.16	0.05	0.13
Germany	**0.45**	0.15	0.04	**0.15**	0.44	0.16	0.04	**0.15**

Greece	0.19	0.04	0.06	0.03	0.23	0.12	0.09	0.05
Hungary	0.36	0.15	0.05	0.09	0.39	0.12	0.01	0.10
Italy	0.33	0.07	0.05	0.10	0.35	0.17	0.01	0.10
Poland	0.36	**0.18**	0.05	0.06	0.42	0.20	0.08	0.08
Romania	0.32	0.15	**0.13**	0.02	0.33	0.14	**0.13**	0.03
Slovakia	0.41	0.16	0.05	0.07	0.42	0.14	**0.13**	0.03
Slovenia	0.40	0.16	0.06	0.11	0.45	0.18	0.07	0.12
Spain	0.40	0.11	0.07	0.07	0.40	0.16	0.04	0.08
Average	0.37	0.14	**0.06**	0.08	0.40	0.16	**0.06**	0.09
Achieved score	74%	70%	**40%**	53%	80%	80%	**40%**	60%

3.4.3. Regional analysis

A regional analysis was performed considering only social and economic indicators and the results differed compared to the country-level analysis, however also similarities were found. In line with the country-level analysis, *Adriatic Croatia* presented the highest improvement. This was to be expected as this was the only Croatian region considered. Once again, the results were skewed by the important regional GDP growth the region experienced in 2022. In fact, the regional GDP of *Adriatic Croatia* grew by 11.3% in 2022 compared to the previous year [43]. For comparison, the highest value in the baseline was 4.7% (Table 4). This high improvement inevitably skews the index in favour of this region. It needs to be said that regional economic growth cannot be firmly causally linked to the fair energy transition, as other factors will inevitably play a role (e.g., in the case of *Adriatic Croatia*; tourism and economic recovery from COVID-19 pandemic). Additionally, regions with a more stable performance, such as German ones, will inevitably be affected negatively. This is indeed one explanation to why German regions performed much better in the baseline compared to 2022 (Table 10). *Düsseldorf* specifically saw its regional GDP growth shrink by 0.5% in 2022 [43]. Even though the present research was not focused on GDP, but rather considered a multitude of other factors not limiting itself to a GDP analysis [18], the latter indicator still played an important role.

Northwestern Czechia being the best performer together with *Greater Poland* in 2022 (Table 10) can be attributed to the former being the region which performed best socially. In particular, *Northwestern Czechia* saw a positive increase in the "living conditions" impact, performing over average. On the other hand, *Greater Poland* presented positive values all around, achieving also a perfect score in the economic dimension. When looking at regions which saw the greatest decrease, *Southwestern Oltenia* stands out. This is due to poor performance in the economic dimension, once again dictated by economic growth as in 2022 the region saw its regional GDP shrink by 3.1% [43]. Finally, in both cases and in all analyses Western Macedonia (and Greece) was found to be the most negatively impacted region by the energy transition, in line with literature [6], [19].

Table 10: Summary of regional analysis results. The net change column shows the difference between the baseline index value and the 2022 index value.

Region	2016-2020 (Baseline) Dense Ranking	2016-2020 (Baseline) Index Value	2022 Index value	Net change	2022 Dense Ranking
Brandenburg	**1**	**0.87**	0.87	0.00	5
Leipzig	**1**	**0.87**	0.86	-0.01	6
Münster	2	0.86	0.84	-0.02	7
Dresden	3	0.85	0.88	0.03	4
Köln	3	0.85	0.84	-0.01	7

Düsseldorf	4	0.84	0.81	-0.03	10
Saxony-Anhalt	5	0.83	0.86	0.03	6
Moravia-Silesia	6	0.82	0.90	0.08	2
Western Slovakia	6	0.82	0.79	-0.02	11
Greater Poland	6	0.82	**0.91**	0.09	**1**
Northwestern Czechia	7	0.81	**0.91**	0.10	**1**
Eastern Slovenia	8	0.80	0.89	0.08	3
Lesser Poland	9	0.79	0.88	0.09	4
Lower Silesia	9	0.79	0.88	0.09	4
Łódzkie	10	0.78	0.86	0.08	6
Aragón	11	0.76	0.83	0.07	8
Silesia	11	0.76	0.90	0.14	2
Macro region 4 West	12	0.74	0.78	0.04	12
Northern Hungary	13	0.73	0.72	-0.01	15
Castilla y León	13	0.73	0.79	0.06	11
Southwestern Bulgaria	14	0.70	0.82	0.12	9
Principality of Asturias	15	0.69	0.76	0.07	13
Lublin	16	0.67	0.86	0.19	6
Adriatic Croatia	17	0.64	0.90	**0.26**	2
Southwestern Oltenia	18	0.61	0.56	**-0.05**	18
Sardinia	19	0.58	0.75	0.17	14
Southeastern Bulgaria	20	0.55	0.63	0.08	16
Peloponnese	21	0.44	0.59	0.15	17
Western Macedonia	**22**	0.22	0.41	0.19	**19**
Average across all regions		0.73	0.80	0.07	

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3.4.4. Overarching analysis of results

The results displayed differences depending on the level of analysis, but also commonalities. Western Macedonia and Greece consistently resulted as the region/country presented highest vulnerability to all considered impacts. This was the same at regional and national level. The inclusion of all dimensions allowed to have a holistic and theoretically sound analysis of how different impacts related to fair energy transitions were affected. Such analysis illustrated however the issues arising when considering national level impacts related to fair energy transitions. On the other hand, a more granular analysis performed by considering only dimensions for which NUTS2 level data was available presented a more focused and pragmatic analysis. In both cases, it was seen how out-of-ordinary performance in one particular impact can skew the results of the analysis. All in all, the efficacy of the index in allowing to

illustrate at the same time how different policy areas will be impacted by the implementation of fair energy transitions was shown. To summarise, Figure 6 illustrates how each dimension changed from the baseline values to 2022. As can be seen, the economic dimension was rather skewed for some countries. On the other hand, the social dimension saw more moderate but positive increases throughout all countries.

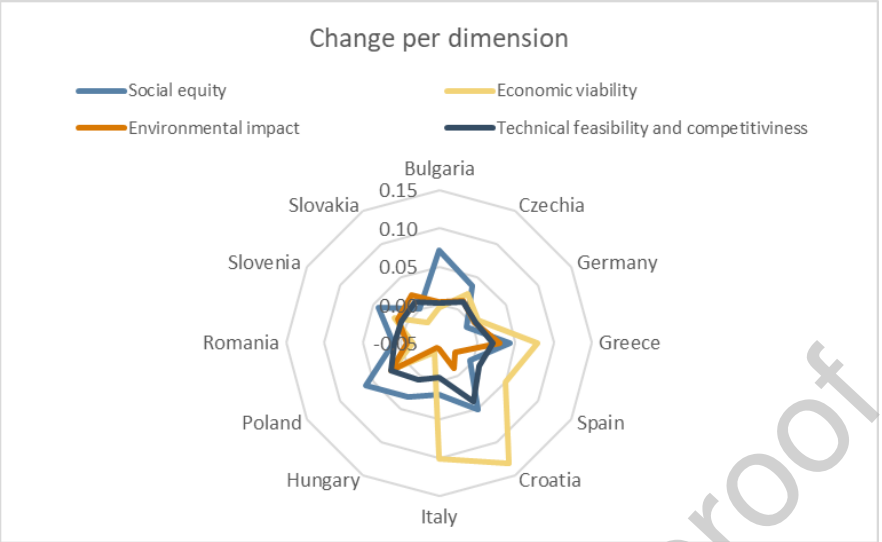

Figure 6: Graphical illustration of how every dimension changed when comparing the baseline to 2022 for every country.

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4. Discussion

The weighting structure highly influences the results. In this research, in line with the adopted definition of fair energy transition, each impact was given the same importance (with minor differences resulting from data granularity issues). Nonetheless, the female unemployment rate and regional GDP growth emerge as the most influential indicators, exerting substantial influence over the overall assessment of transition performance. Whereas this is due to the fact that both indicators fully represent one impact; it must be noted that female unemployment also underscores persistent gender disparities within transitioning labour markets, where structural barriers to female workforce participation remain pronounced due to the historically male-dominated nature of the coal industry [44]. In fact, female unemployment does not fully reflect all gender implications. More indicators should be utilised to quantify all the social issues related to the gender dimension. On the other hand, the emphasis on regional GDP growth as a key determinant of transition performance reinforces the critical role of economic resilience in mitigating transition shocks. Whereas economic performance of

a region is vital in alleviating the negative impacts resulting from the energy transition and thus needs to be considered as regions performing better economically will inevitably be more resilient to energy transition shocks; GDP growth does not guarantee an inclusive or sustainable transition. Economic expansion may improve overall resilience, but without deliberate policy intervention, it risks bypassing vulnerable groups and neglecting environmental objectives. Additionally, an improvement in economic growth cannot be explicitly attributed to a positive implementation of the fair energy transition. The role of policy is therefore essential to direct growth in a way that reduces inequalities, promotes clean technologies, and ensures that the benefits of growth are equitably distributed across society.

Policy makers and regional authorities can utilise the FETI to have an initial holistic understanding of how their region is affected by different fair energy transition impacts. In fact, the tool allows to understand which impacts have positive or negative trends in the region. The EGD calls for a transition that is fair [1], and thus related policy measures should not be focused merely on one dimension. Policies are often delineated without any quantitative analysis justified by regional data unavailability. The present tool can direct where data collection should be prioritised and highlight which dimension is more vulnerable depending on the region. As part of the JTF, regions need to delineate territorial just transition plans [2]. As seen in [6], certain impacts are highly prioritised compared to the rest (namely unemployment in particular). The present index can also aid policy makers in better understanding the policy direction such plans should undertake. Fair transition strategies frequently prioritise economic stability and social protection, reflecting the immediate political and economic concerns of coal-dependent regions [6]. The FETI can help policy makers to advocate for more structured long-term measures that affect the region in a more holistic way, targeting all the different dimensions.

Applying targets at a regional level is vital to achieve national level targets. This can be applied also to the Sustainable Development Goals (SDG) delineated by the United Nations (UN). The indicators hereby utilised also help in tracking the achievement of SDGs (e.g., SDG3 good health and well-being, SDG9 industry, innovation, and infrastructure, and SDG11 sustainable cities and communities). In fact, the UN also utilises data from the Eurostat repository at NUTS2 level to monitor the targets [45]. Additionally, the methodology hereby employed is also similar to the one employed by the UN, as first extreme values were taken out, then the indicators were normalised (with the best performing one having a value of 100) to be compared between each other, and thereafter they were aggregated to create an overall index score [45]. When it comes to regional performance, the results are in line with other studies in literature, finding Western Macedonia as the worst-performing coal region, with Southwestern Oltenia and Southeastern Bulgaria being amongst the worst performing regions [19]. Finally, whereas other studies have utilised MCDA in the context of energy transitions [46], [47], the present one is the first one to employ it for assessing the degree to which coal regions are implementing a fair energy transition across the EU.

5. Limitations and further research

Despite the robustness of the proposed FETI, certain limitations must be acknowledged. One primary limitation stems from data availability and granularity. The reliance on Eurostat as the primary data source ensures methodological consistency across EU regions [24]; however, it also limits the precision of regional assessments due to the lack of NUTS2-level data for key indicators. Household Budget Surveys could provide more localised data. Nonetheless, this type of data often relies on questionnaires and surveys; with the methodologies used for gathering them varying across MS [24]. Additionally, such surveys require expertise and resources, making it a lengthy process, with the quality

of the data being dependent on the interviewee answers, and on the frequency of the survey's conduction [24]. The FETI can direct policy makers towards which policy area necessitates more localised data per region. In fact, all the considered environmental and technical indicators are only available at the national level, reducing their applicability for assessing transition impacts at the regional scale. At the same time, it was preferred to use data that was not the result of approximations or assumptions, to maintain data correctness, as average and aggregate data mask issues [24]. Additionally, temporal constraints restrict the ability to conduct a fully dynamic analysis, as complete post-2022 data is not yet available to assess the evolving effects of the JTF. Future research should explore integrating alternative data sources, such as national statistical offices, environmental agencies, and satellite-based monitoring, to enhance the resolution and precision of environmental impact assessments.

Another key limitation relates to the static weighting of indicators within the index. While the chosen weight distribution ensures methodological coherence, considering all dimensions and being corroborated by a sensitivity analysis, it does not fully capture the evolving dynamics of transition priorities across different regions. By applying the same importance to all impacts, the ones quantified by only one indicator, such as female unemployment and regional GDP growth, inevitably provide higher relative weight to that one indicator. This results for example in regions having high economic growth performing extraordinary well. One solution would be not to have any impacts quantified by only one indicator. Nonetheless, these impacts were still considered given their importance in a fair energy transition. Reducing their weight could risk overlooking critical social and economic dimensions that are central to a fair transition. When considering environmental impacts specifically, the ones quantifying regional energy efficiency, renewable energy production, and import dependence should be prioritised [39]. Furthermore, indicators such as the building energy performance, share of green industry, and indoor and outdoor air quality should be also considered at regional level [48]. Future research should consider adaptive weighting mechanisms that allow environmental factors to gain greater prominence as policy priorities shift towards climate neutrality.

Further research should also focus on integrating predictive modelling and scenario-based assessments. The current approach offers an ex-post analysis of transition impacts, but incorporating machine learning models or econometric forecasting techniques could enable the simulation of future transition pathways, particularly in the environmental domain. Machine learning methods, such as supervised learning, could be used to model the relationship between historical transition indicators and outcomes, allowing for predictions of future regional performance under different policy scenarios, but also in weighting the impacts [41]. Additionally, unsupervised learning techniques, such as clustering, could help identify groups of regions with similar transition profiles, enabling more targeted and context-specific policy design. These models could enhance policymakers' ability to anticipate emerging risks, including emissions rebound effects, regional climate vulnerabilities, and energy security concerns. Although energy security is not currently included in the set of transition indicators, it is gaining importance, particularly where the replacement of coal with imported natural gas may introduce new forms of dependence.

6. Conclusion

The hereby developed FETI allowed to assess how different impacts related to the implementation of a fair energy transition in EU coal regions have changed over time. To do so, a baseline time period was compared to the year 2022. The FETI considered impacts from different dimensions, giving equal importance to all impacts in line with the postulated definition of fair energy transition. Data

unavailability at regional level was an important issue, as indicators pertaining to the environmental and technical dimensions were available only at national level. To account for such data granularity issues, only two dimensions were considered when performing regional level analyses. On the other hand, all dimensions were considered for country-level and dimensional analyses. Due to certain impacts presenting only one indicator to quantify these, certain indicators held higher weight within the index. This partially skewed the results in instances where certain regions presented out-of-the-norm improvements. This was the case particularly with the regional economic growth impact. The worst-performing coal region was found to be Western Macedonia followed by the Peloponnese, making Greece the worst-performing country when it comes to implementing a fair transition in coal regions. A total of 29 coal regions from 12 EU countries were considered.

The FETI allows for policy makers to have a more holistic understanding of how different fair energy transition impacts affect the region and allows for a cross-region but also cross-country comparison of results. The developed index can greatly help policy makers and regional authorities to understand towards which policy area improvements and measures should be directed, and which type of regional data should be collected to have a better implementation of a fair energy transition within the region. The data utilised was gathered from the Eurostat repository. Hence, with the latter being updated regularly, such analysis can be repeated for every year to come, making it possible to compare different timelines. The FETI can also help policy makers in monitoring different indicators from different dimensions, in line with other known policy frameworks.

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Annex

Sensitivity analysis was conducted using the five-year average (2016–2020) for all indicators, as it reflects the most recent pre-transition conditions across regions. This approach ensures robustness of the index results under different weighting assumptions, while avoiding year-specific volatility. The results comparison is shown in Table 11.

Table 11: 2022 scores and score changes under different weighting scenarios.

Region	Chosen scenario	Equal weights per dimension	Equal weights per criterion	Economic-dominant	Environmental-dominant	Technical-dominant	Extreme social	Maximum change:
Southeastern Bulgaria	0.54	0.46	0.52	0.46	0.50	0.35	0.63	0.28
Southwestern Bulgaria	0.68	0.60	0.64	0.70	0.59	0.44	0.72	0.29
Northwestern Czechia	0.81	0.73	0.79	0.75	0.59	0.78	0.90	0.30
Moravia-Silesia, Czechia	0.81	0.73	0.79	0.75	0.59	0.78	0.89	0.29
Brandenburg, Germany	0.81	0.76	0.80	0.79	0.60	0.86	0.86	0.26
Düsseldorf, Germany	0.77	0.72	0.76	0.71	0.57	0.83	0.83	0.26
Köln, Germany	0.79	0.74	0.77	0.75	0.59	0.85	0.84	0.26
Münster, Germany	0.79	0.74	0.77	0.75	0.58	0.85	0.84	0.26
Dresden, Germany	0.82	0.77	0.80	0.80	0.60	0.87	0.85	0.26
Leipzig, Germany	0.80	0.75	0.79	0.77	0.59	0.86	0.85	0.26
Saxony-Anhalt, Germany	0.80	0.75	0.79	0.77	0.59	0.86	0.85	0.26
Western Macedonia, Greece	0.43	0.43	0.43	0.41	0.48	0.41	0.44	0.08
Peloponnese, Greece	0.56	0.57	0.55	0.65	0.57	0.49	0.51	0.15
Asturias, Spain	0.66	0.59	0.64	0.65	0.49	0.58	0.71	0.22
Aragón, Spain	0.71	0.62	0.68	0.67	0.51	0.60	0.79	0.27
Castilla y León, Spain	0.68	0.61	0.65	0.66	0.50	0.59	0.74	0.24
Adriatic Croatia	0.81	0.79	0.79	0.91	0.76	0.68	0.77	0.22
Sardinia, Italy	0.63	0.57	0.60	0.64	0.40	0.60	0.67	0.28
Northern Hungary	0.61	0.51	0.58	0.53	0.36	0.57	0.72	**0.36**
Lesser Poland	0.78	0.71	0.75	0.77	0.65	0.65	0.83	0.18
Silesia, Poland	0.79	0.73	0.77	0.81	0.66	0.67	0.83	0.17
Greater Poland	0.80	0.74	0.77	0.81	0.66	0.67	0.83	0.17
Lower Silesia, Poland	0.77	0.71	0.75	0.77	0.65	0.65	0.82	0.17
Łódzkie, Poland	0.76	0.70	0.74	0.77	0.64	0.65	0.80	0.16
Lublin, Poland	0.76	0.71	0.74	0.79	0.65	0.65	0.79	0.14
Southwestern Oltenia, Romania	0.55	0.52	0.55	0.49	0.64	0.43	0.60	0.21
Macro Region 4 West, Romania	0.71	0.69	0.69	0.77	0.74	0.53	0.69	0.24
Eastern Slovenia	0.81	0.76	0.79	0.79	0.66	0.78	0.86	0.20
Western Slovakia	0.71	0.64	0.69	0.66	0.60	0.61	0.79	0.18

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The chosen scenario produces results that closely align with the equal weights per criterion scenario, with a maximum score deviation of only 3%. This minimal difference results in a shift of no more than two positions in the dense ranking, with 48% of regions retaining their original position and another 48% improving by a single rank under the chosen weighting.

By contrast, the greatest divergence occurs between the environmental-dominant and extreme social scenarios, where regions experience an average drop of six ranks under the latter. This illustrates how substantial shifts in weighting priorities can meaningfully alter the perceived fairness landscape.

Notably, in the transition from the chosen to the environmental-dominant scenario, the four highest-ranked regions experience a decline in rank, while 13 of the lowest-ranked regions move upward. This pattern suggests that environmentally focused weighting tends to favour structurally weaker or more vulnerable regions, whereas regions that perform strongly on social criteria lose their relative advantage when environmental priorities are emphasized.

Although several socially and economically disadvantaged regions demonstrate stronger performance under the environmental-dominant scenario—indicating structural characteristics or emerging progress aligned with green priorities—these gains are insufficient to outweigh their broader social and economic deficits. This underscores the structural disadvantage these regions face: even with positive developments in environmental performance, enduring social vulnerability prevents them from achieving higher overall rankings in more balanced or socially weighted scenarios.

Notable observations from Score Volatility

Northern Hungary stands out as the most volatile region, with a score range of 36% across scenarios. Sardinia, and Bulgarian and Czech regions follow with 28%-30% volatility. This unusually high volatility reflects extreme sensitivity to the environmental dimension, since these regions perform the lowest in the risk and vulnerability to climate impacts, specifically they are the lowest performers in the LULUCF and Climate related economic losses.

This volatility could also imply that their profile is balanced between social vulnerability and environmental/technical progress, and thus particularly responsive to how dimensions are emphasized.

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Declaration of interests

☒ 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.

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