When does the energy transition impact household affordability? A mixed-methods comparison of fourteen coal and carbon-intensive regions

Martinez-Reyes, Amanda; Lieu, Jenny; Goyal, Nihit; Mangalagiu, Diana; Hoppe, Thomas

DOI
10.1016/j.gloenvcha.2024.102936

Publication date
2024

Document Version
Final published version

Published in
Global Environmental Change

Citation (APA)
Martinez-Reyes, A., Lieu, J., Goyal, N., Mangalagiu, D., & Hoppe, T. (2024). When does the energy transition impact household affordability? A mixed-methods comparison of fourteen coal and carbon-intensive regions. *Global Environmental Change*, *89*, Article 102936. https://doi.org/10.1016/j.gloenvcha.2024.102936

Global Environmental Change 89 (2024) 102936

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

When does the energy transition impact household affordability? A mixed-methods comparison of fourteen coal and carbon-intensive regions

Amanda Martinez-Reyes [a,*], Jenny Lieu [a], Nihit Goyal [a], Diana Mangalagiu [b], Thomas Hoppe [a]

[a] Technology Policy and Management, Delft University of Technology, the Netherlands
[b] Neoma Business School, France

ARTICLE INFO

Keywords:
Coal and carbon-intensive regions
Energy affordability
Just transitions
Sociotechnical transitions
Regional energy governance
International policy mixes

ABSTRACT

Understanding what conditions promote or hinder energy affordability in energy transitions is crucial for coal and carbon-intensive regions (CCIRs) dealing with the trade-off between phasing out fossil fuels and deepening social inequalities. While previous studies have included household and national-level conditions, this paper addresses the research gap covering regional-level conditions by drawing from regional energy governance, energy justice, and sociotechnical transition frameworks. A mixed-method approach consisting of a fuzzy-set qualitative comparative analysis and case-study analysis is applied to 14 CCIRs in Europe, Asia, and North America. Results show that energy affordability in CCIRs is influenced by combinations of regional and (inter) national conditions. Whereas the existing literature and transition policies do not differentiate between the CCI sector's transition type, this paper highlights that conditions underlying energy (un)affordability differ when the CCI sector is phased out or has the option to transition. Based on the findings, this study calls for a multi-level governance approach to alleviating and preventing energy unaffordability and recommends that policy mixes like the EU Just Transition Fund consider the different types of CCIR transitions.

1. Just transitions and energy affordability in coal and carbon-intensive regions

The Intergovernmental Panel on Climate Change has recognized that energy transitions could worsen socioeconomic inequalities unless justice is embedded into their design (IPCC, 2018). This acknowledgment has contributed to increasing scholarly attention to just energy transitions (Heffron, 2022; McCauley et al., 2013; McCauley and Heffron, 2018; Wang and Lo, 2021).

Energy affordability is a key dimension of a just energy transition and has received attention in two major energy justice frameworks. First, the tenets framework distinguishes among recognition of marginalized voices, distribution of benefits and losses, and procedural inclusion of diverse stakeholders in the energy transition (Heffron, 2022; McCauley et al., 2013; McCauley and Heffron, 2018) (Bouzarovski and Simcock, 2017; del Guayo and Cuesta, 2022; European Commission, 2018; LaBelle et al., 2023; Snell, 2018; Wang and Lo, 2021). Second, the classification of energy justice based on eight main dimensions: Affordability, availability, due process, information, sustainability, intragenerational equity, intergenerational equity, and responsibility (González-Eguino, 2015; Sovacool et al., 2017, 2016; Sovacool and Dworkin, 2015).

Coal and carbon-intensive regions (CCIRs) are subnational territories with socioeconomic dependence on fossil-fuel sectors, which can cause or accentuate energy unaffordability when pursuing a low-carbon energy transition. CCIRs can be classified as *upstream* sectors where fossil fuel resources are extracted (e.g., coal mining, oil or gas extraction) or as *downstream* sectors where fossil fuels or fossil-fuel-generated energy are intensively used as input for industrial processes (e.g., steel production) (European Commission, 2018; Martinez-Reyes et al., 2021, p. 5). Energy transitions in CCIRs come with socioeconomic impacts, as jobs, livelihoods, and shared identity can be tied to the industrial sector (ECA, 2022; Martinez-Reyes et al., 2021). Thus, the transition or decline of CCI sectors may impact the energy affordability of households at the regional level, making just transitions particularly difficult to achieve in CCIRs. This challenge has received political attention around the world, for instance, in the European Union (EU) (European Commission, 2021a; European Parliament and Council, 2021) and Canada (Government of Canada, 2018).

A regional governance level is necessary for the transition of CCIRs. Governance of energy systems refers to a collection of ways in which groups of (energy sector) actors, both formal and informal decision-

* Corresponding author.
E-mail address: a.martinezreyes@tudelft.nl (A. Martinez-Reyes).

https://doi.org/10.1016/j.gloenvcha.2024.102936
Received 5 August 2023; Received in revised form 26 August 2024; Accepted 18 September 2024
Available online 2 October 2024

makers, organize themselves and make decisions about the distribution of energy resources and provision of energy services (Florini, 2013; Florini and Sovacool, 2009). Energy governance is affected by decision-making bodies at different levels and with varying powers of decision-making, like the local (e.g., municipal), regional (e.g., provincial), national, and international levels (e.g., EU-level). Particularly, a regional governance level is essential to address regional transition challenges, like socioeconomic dependency on a fossil-fuel sector, which are not represented in national policies but are shared by multiple municipalities.

Comparative studies have been conducted to understand the drivers of energy affordability in multiple cases. Qualitative Comparative Analysis (QCA) has been applied as a methodology for comparison as it can consider theoretical expectations in the analysis and capture the interdisciplinary, quantitative, and qualitative nature of transitions in a medium-size number of cases (N=10–100) (Ragin, 2009). A few QCA studies have analyzed the drivers of energy affordability (Primc et al., 2019a, 2019b).

Yet, two research gaps remain in the comparison of energy affordability (Bouzarovski and Simcock, 2017; Martiskainen et al., 2021; Wang and Lo, 2021). First, although previous research has shown that geographic inequities entrenched in (regional) energy systems can cause injustices such as energy poverty (Bouzarovski and Simcock, 2017), studies focusing on the latter have prioritized either household or national-level factors, leaving a disconnect with the regional scale (Bouzarovski and Tirado Herrero, 2017; González-Eguino, 2015; Primc et al., 2019b, 2019a; Primc and Slabe-Erker, 2020). To our knowledge, no peer-reviewed study has analyzed the causal relationship between macro- and mesolevel (or regional-level) conditions and energy affordability. Second, while the energy justice literature has differentiated between regional influence in the case of energy production and consumption (Jenkins et al., 2016), thus far, no study has explored upstream and downstream CCIRs (Wang and Lo, 2021). Arguably, a key reason for these gaps and limitations is the logistical and methodological complexity of collecting data from numerous regional cases and systematically analyzing a large and varied dataset.

Therefore, to address those gaps, this study analyzes the meso- and macrolevel conditions that assumably influence energy affordability in fourteen CCIRs. We think the coverage of meso- and macrolevel conditions can improve one's understanding of energy affordability in CCIRs (Kimbrell, 2022).

The contribution of this paper is twofold: theoretically, by identifying regional conditions that influence energy affordability, and empirically, by comparing energy affordability in different CCIR contexts, such as upstream and downstream regions (European Commission, 2018). Further, policymakers and practitioners in CCIRs could benefit from a better understanding of the possible impacts of transitions on affordability across different regions.

The paper is structured as follows: Section 2 introduces the theoretical framework and the selected conditions, followed by the research design and methodology section in Section 3. Section 4 presents the QCA solutions and discussion based on the qualitative case-study approach of three CCIR examples. Section 5 presents the conclusion and contribution of this study to relevant academic debates on the development of comparative methods and energy affordability alleviation policies. This section also presents limitations, a future research agenda, and policy recommendations.

2. Theoretical framework: Energy affordability and its conditions in CCIRs

Energy affordability has been defined as "the ability of households to purchase a necessary quantity of energy or level of energy services (to reach thermal comfort and to be able to fulfill daily activities) without suffering undue financial hardship" (Dubois and Meier, 2016p. 22; Kessides et al., 2009). It is the most commonly studied and operationalized dimension of energy poverty (Bonatz et al., 2019; Che et al., 2021; Pereira et al., 2021), a multidimensional construct also incorporating energy access and availability (Bouzarovski and Petrova, 2015; Villalobos et al., 2021). Energy affordability has been *measured* with indicators (Bonatz et al., 2019; Che et al., 2021; Pereira et al., 2021).

The drivers for energy affordability can be categorized into aggregation levels, such as macrolevel (international and national), mesolevel (regional or subnational), and microlevel (household) (Dubois and Meier, 2016). Some commonly reported drivers for energy affordability are defined at the microlevel, such as household efficiency and income, and at the macrolevel such as energy prices, energy services deprivation, and policies (Bonatz et al., 2019; Dubois and Meier, 2016; Rademaekers et al., 2016).

Previous QCA studies focused on energy poverty also covered macrolevel conditions such as gross domestic product, type of climate, energy prices to final consumers, energy poverty policies, and microlevel ones like household ownership status, education level, labor force status, household size, type of building, central heating system, and the presence of solar collectors and heat pumps (Primc et al., 2019a, 2019b). This study concluded that energy poverty arises from a combination of poor energy-inefficient households (microlevel) and labor market problems (macrolevel) (Primc et al., 2019a). Nonetheless, drivers at the meso- or regional level remain underexplored.

2.1. Conditions for energy affordability

A literature review was conducted to discern relevant conditions for energy affordability as dependent on selected conditions at the regional, national, and international levels. This review covered the main research domains related to energy justice (McCauley et al., 2019) and energy poverty (González-Eguino, 2015; Nussbaumer et al., 2012) as overarching frameworks that explain energy affordability and socio-technical transitions (Geels, 2019, 2002; Köhler et al., 2019; Markard et al., 2012) and regional energy governance (Hoppe and Miedema, 2020; Smith et al., 2005). Moreover, findings from a research project that focused on the energy transition of CCIRs were considered to identify contextual conditions for energy affordability (reference to be provided upon acceptance).

2.1.1. CCIND: Regional economic independence from the coal and carbon-intensive sector

The first selected condition for the fs-QCA was regional economic independence from coal and carbon-intensive sectors (Cha et al., 2020). CCI upstream sectors like coal mining and oil and gas extraction, and downstream sectors like the chemical industry and steel and cement production can be important to a region's economy. For example, employment in coal mining sectors can create new towns and cities. Still, dependency on the industry can also lead to a population decline once the sector shrinks or shuts down, as seen in the case of Carbonia, Sardinia, in Italy (Pau et al., 2022). Upstream coal-mining regions are among the most negatively impacted by energy transitions due to potential job losses and economic decline (European Commission, 2018, 2021a; Government of Canada, 2018). These impacts can directly affect the socioeconomic well-being of households in the region, including energy affordability (Cha et al., 2020). Similarly, regions dependent on downstream carbon-intensive economic sectors such as steel, chemical, or cement production may present a low level of economic diversification and, therefore, be negatively impacted when CCI sectors shrink as a result of a sectoral transition (European Commission, 2018).

Regional diversification theories help describe the relationship between CCI sector economic independence and energy affordability. Indirectly, when a region is economically independent of a CCI sector, this may indicate that the region has more economic diversity than when a CCI sector is dominant in the region. However, this does not hold true when the region suffers high unemployment, outmigration, and other socioeconomic struggles due to the decline of the CCI sector. These theories suggest that regions with higher economic diversity experience lower unemployment and more stable economic growth as more diverse economic sectors can absorb a sector's unemployment by another sector, if sectors do not fluctuate simultaneously (Malizia and Ke, 1993). Yet, economic diversity and growth do not have a linear relationship (Malizia and Ke, 1993; Siegel et al., 1995). Regional diversification studies also distinguish between economic diversity and diversification. The latter refers to the process of diversifying the economy (Siegel et al., 1995), which is the case for transitioning CCIRs. Therefore, it can be hypothesized that a high degree of regional economic independence from the CCI sector increases the likelihood of households having energy affordability when the region undergoes a sectoral transition.

2.1.2. TECHFEA: Technical feasibility of the CCI's sector transition

The type of transition a CCI's sector follows impacts household energy affordability. According to transition studies and regional diversification theory, a region can experience *related* or *unrelated* diversification or an on-stream or off-stream pathway (Boschma et al., 2017; Lieu et al., 2020). Regional diversification can be related to existing sectors and institutions, also described as an 'on-stream transition pathway'; for example, when the same electric utility replaces coal-based with renewable-energy-based power generation with no significant changes in institutions and actors. Alternatively, diversifications can be unrelated to the previously dominant sector, for example, when the region shuts down coal mines and promotes tourism (Boschma et al., 2017). Related diversification and on-stream pathway transitions are the dominant approaches adopted in regions due to the transferability of capabilities, infrastructure, skills, and institutions. These on-stream pathway transitions have a lower risk of closing operations and causing unemployment. However, both types of diversification, related and unrelated, are needed for the long-term economic stability of a region because relying on related diversification can only lead to path dependency and lock-ins (Boschma et al., 2017). Thus, this hypothesis states that CCI sectors with the technical possibility to transition will affect less households' income and so energy affordability than CCI sectors that cannot find or develop the technical feasibility to transition.

2.1.3. Decarbonization of the regional energy system

The level of decarbonization of the regional energy system can affect energy affordability. Deploying low-carbon/renewable energy technologies is necessary to phase out fossil-fuel-based power and heating generation. Without affordable alternatives for energy generation, energy prices can increase and affect households' energy affordability. For example, a study in the United Kingdom showed that a rapid energy system decarbonization does not necessarily help alleviate energy poverty (Nolden et al., 2022). Several studies have revealed that distributed generation from renewable energy sources is positively related to energy poverty alleviation in Western and majority world countries (Pagliaro and Meneguzzo, 2020; Ramos et al., 2022). A distributed energy system with renewable energy technologies may perform better on energy justice compared to a centralized energy system (Banerjee et al., 2017). However, community ownership and incentives for low-income households are essential to bridge the energy poverty gap (Sovacool et al., 2016). Thus, a high degree of decarbonization can lead to energy affordability if there is local energy ownership, but it can also affect energy affordability in regions where the costs of decarbonization are high and transferred to citizens.

2.1.4. International policy mixes

A multi-level governance approach to the energy transition is required to meet and align objectives at different administrative levels (Hermanson, 2018). Particularly, in CCIRs, external influences like energy market prices can halt a low-carbon transition, depending on the country's type of energy system, its technologies, and whether it is a net exporter or importer. For example, the 2022 natural gas price surges left many European residents with unaffordable energy bills due to the Russian-Ukraine conflict escalation commencing in February 2022. This international event clearly shows the impact that a fossil-fuel-dependent energy system can have on energy affordability.

In response, several countries (e.g., the Netherlands) issued and implemented policy mixes, including price compensations, subsidies, and energy caps (Ministerie van Algemene Zaken, 2022; Yagi and Managi, 2023). Additionally, the European Union launched the REPowerEU program in 2022, aimed at reducing members' dependency on Russian fossil fuel imports and boosting the adoption of renewable energy technologies by 2030 (EU, 2022). These policy mixes at the national and international levels can influence the course of regional energy transitions and impact (positively or negatively) households' energy affordability through energy prices, subsidies, etc. Therefore, it can be hypothesized that for (inter)national policy mixes to ensure a positive impact on energy affordability, they need to align with regional energy transition efforts and consider dimensions of energy poverty, for example, the EU-level energy poverty initiatives (Bouzarovski et al., 2012).

2.2. Conditions and their proxy indicators

A list of four conditions that can lead to regional energy affordability was used as the theoretical framework for the fs-QCA. Three of these conditions are defined at the regional level, including the 1.1 level of CCI independence, 1.2 regional decarbonization level, and 1.3 technical transition feasibility of the CCI sector. The fourth condition is defined at the national and international levels, the 2.1 impact of (inter)national policy mixes in the regional energy transition. Other conditions like regional innovation, transition strategy, polycentricity, market competition, market price fluctuations, and an energy region's degree of polycentricity were initially considered but later disregarded to meet the maximum number of conditions and because some conditions do not have a straightforward logical relationship with energy affordability and others were considered less influential for our set of cases. The operationalization of each condition is described in detail in Table 1.

3. Mixed-methods approach: Fs-QCA and case-study analysis

The most common methods to assess energy affordability are statistical analyses (Bonatz et al., 2019; Che et al., 2021; Pereira et al., 2021; Villalobos et al., 2021). For example, a recent study analyzed the conditions for energy and transport poverty using descriptive statistics

Table 1
Operationalization of dimensions with proxy indicators.

Outcome (code)	Conditions (code)	Expected influence on the outcome
Energy affordability of households in the region Indicator:Percentage of household income spent on energy services (electricity and heating) at the regional level, median value from 2012 to 2022 (MEAFFO)	1.1 Level of regional economic independency from the CCI sector up to 2022 (CCIIND)	Positive: The more CCIIND, the more household energy affordability.
	1.2 Level of decarbonization based on the regional power generation, median value of 2012–2022 (DECA)	Positive: The more DECA, the more household energy affordability if there is local energy ownership.
	1.3 Degree of technical feasibility for the CCI sector transformation in the region up to 2022 (TECHFEA)	Positive: The more TECHFEA, the more household energy affordability.
	1.4 Level of positive impact of (inter)national policy mixes on the regional energy transition, up to 2022 (NATINTPOL)	Positive: The more NATINTPOL, the more household energy affordability.

and regression analysis of national surveys in four cases (Furszyfer Del Rio et al., 2023). However, statistical analyses can have limitations when it comes to analyzing complex phenomena, including interdependence among variables, relatively large case samples, difficulty in handling non-linear relationships, and the consideration of empirical or theoretical knowledge in the analysis. QCA is considered a robust method that can help understand the non-linear casual relationships between conditions and the outcome while considering theoretical assumptions in the analysis (Mello, 2021). In particular, fuzzy sets (fs-QCA) are helpful in giving nuanced qualitative meaning to the values of variables or the membership of sets (Ragin, 2023, 2009).

A mixed-method approach was adopted to explore the relationships between conditions for energy affordability in CCIRs. Fs-QCA was chosen as it allows for a configurational analysis that combines qualitative and quantitative elements, intrinsic of just transition studies (Marx, 2010; Ragin, 2009, 1987; Schneider and Wagemann, 2012, 2010). Then, fs-QCA was combined with qualitative case study analysis to gain an in-depth understanding of causal relationships between conditions and the outcome. Fourteen cases and four conditions were selected to identify the configurations that lead to energy affordability, as described below. Next, the fs-QCA intermediate solutions (combinations of conditions linked with) were analyzed for high and low energy affordability and validated with three in-depth case studies. Finally, the findings were discussed according to current debates on energy affordability and poverty, especially concerning regional energy transitions.

3.1. Case selection

Cases were selected using a purposive sampling strategy (Quinn Patton, 2014). A diverse range of cases representing seventeen CCIR contexts and variations in energy affordability was included. However, at a later stage, this number was reduced to fourteen due to a lack of accessible and consistent data. As presented in Fig. 1 and Table 2, four regions were non-European, and two were from majority-world countries (Mexico and Indonesia); the rest covered regions recognized by the European Commission as CCIRs (European Commission, 2018). Nine regions had upstream CCI sectors, with seven coal mining and two oil extraction (Alberta and Northern Norway). The case of Northern Norway, up to 2022, had not started the exploration of oil resources, although the narrative for its exportation has been a highly disputed issue since 2008 (Karlsson and Dale, 2019). Five regions are home to downstream carbon-intensive sectors such as steel production and power generation using fossil fuel energy sources.

Table 2
CCIR cases included in the fs-QCA.

Upstream CCIRs (Code: NUTS2, NUTS1)	Upstream CCI sector	Downstream CCIRs (Code: NUTS2, NUTS1)	Downstream CCI sector
CZ: Moravian-Silesian, Czech Republic	Coal mining	AT: Upper Austria, Austria	Coal consumption for steel production
DE: Düsseldorf (Essen and Duisburg), Germany	Coal mining	BES: Balearic Islands, Spain	Fossil fuel consumption for power generation
GR: Peloponnese (Megalopolis), Greece	Coal mining	IDN: Bali, Indonesia	Fossil fuel consumption for power generation
TES: Aragon (Teruel), Spain	Coal mining*	GREE: Greenland, Denmark	Oil consumption for back-up heating and power generation
IT: Sardinia (Sulcis), Italy	Coal mining	MX: Baja California, Mexico	Natural gas and diesel for power generation
NO: Northern Norway (Lofoten), Norway	Potential for oil extraction		
PO: Śląskie (Upper Silesia), Poland	Coal mining		
RO: Vest (Jiu Valley), Romania	Coal mining		
CA: Alberta, Canada	Oil extraction**		

*Teruel region also has fossil-fuel-based power generation; however, only the evolution of the coal mining sector was considered in this study.
** Alberta's energy sector also largely relies on gas and coal; this study mainly considered the oil sector.

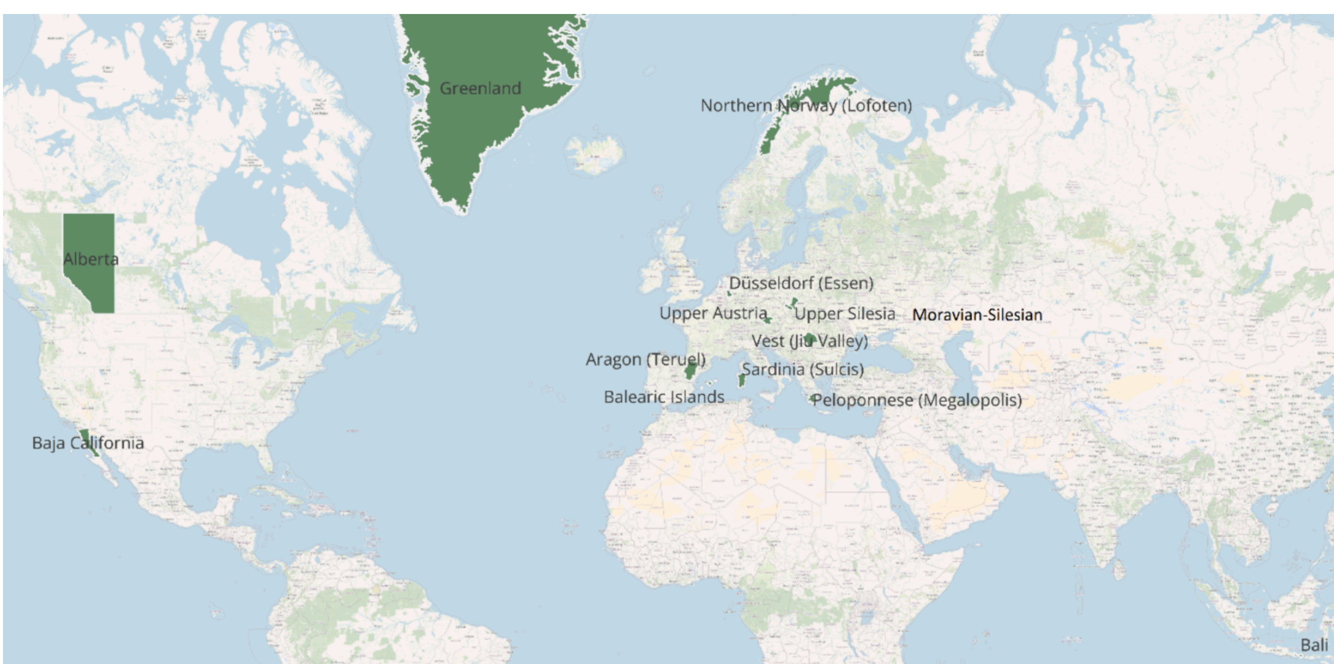


Fig. 1. Map of the CCIRs included in the study.

3.2. Data selection

The assigned fuzzy values, presented in Table 3, of three conditions were obtained from a research project on CCIRs and expert validation (conditions 1.1, 1.3, 1.4, and, for some cases, 1.2). For condition 1.2, public databases such as Eurostat and IEA were used mainly (Eurostat, 2023, 2020; IEA, 2023, 2020).

3.2.1. Measuring energy affordability

The most used indicators for energy affordability are objective and composite indicators with or without weighing factors (Bonatz et al., 2019; Che et al., 2021; Pereira et al., 2021; Villalobos et al., 2021). The 10 % energy expenditure threshold has been widely applied to measure the number of energy-poor households even though it fails to account for households with low energy consumption due to energy poverty (Boardman, 1991; Ntaintasis et al., 2019). Some limitations of this indicator are that the 10 % threshold is context-dependent, which was originally defined for the UK in the early 1990 s, and that it does not show the income level of households (Romero et al., 2018). Yet, the advantages of the 10 % indicator are its relatively simple calculation, its ease to be communicated, and the availability of data for its calculation, which makes it accessible for case comparison studies (Romero et al., 2018). Other indicators of energy affordability are minimum income standards (MIS), which calculates a household's net residual income after energy expenses and living costs (Moore, 2012), and the low income/high cost (LIHC) indicator, which considers a high/low income threshold of the 10 % indicator. These two indicators, however, require additional data like household income level and living costs that can be difficult to collect.

The outcome' energy affordability' (MEAFFO) was measured as the median value from 2012 to 2022 of an average household's energy expenditure. Calculating the number of households in energy poverty (with energy expenditure over 10 % of the household's income) as the standard indicator (Boardman, 1991; Ntaintasis et al., 2019) was not possible due to a lack of data. Thus, the values for an average household were obtained instead. The median value was chosen because it is less affected by the extremes and can better represent a non-symmetrical distribution than a mean value. However, a sensitivity test was performed by comparing the results using the median and the average outcome values, resulting in no difference. The formula for the outcome is shown in equations 1–3, where the household's energy consumption was considered an input variable. The total household sector's energy consumption for electricity and heating at the NUTS-2 level was obtained from the 'Ffe' database, an independent energy research organization that calculated energy demand as described by Pellinger et al., 2019 (Pellinger et al., 2019; Opendata ffe, 2020). The energy prices at the NUTS-1 or country level were gathered from the Eurostat database for the EU regions and official government websites for the other regions (see Appendix A). Since the energy consumption of 2017 (the median of the range of years) was available for all cases, this value was taken as fixed from 2012 to 2022. However, this can overlook a growing energy demand in the household sector.

However, some dimensions related to the affordability of energy services were not considered; for example, households' thermal insulation or access to efficient energy technologies (González-Eguino, 2015; Pereira et al., 2021).

$$MEAFFO = median(x_i) \tag{1}$$

$$x_i = \frac{HEX_i}{HI_i} = \frac{household's\ expense\ in\ energy\ services\ in\ year\ i\ (€)}{household's\ income\ in\ year\ i\ (€)} \times 100\ \% \tag{2}$$

Table 3
Generation of fuzzy values for the outcome and conditions.

Dimension	Indicator	Levels and related fs-QCA values	Fuzzy values
Outcome: energy affordability	Median of the percentage of household income spent on energy services (electricity and heating)	A. The percentage of household income spent on energy services over the last 10 years is less or equal to 3.33 %. B. The percentage of household income spent on energy services over the last 10 years is between 3.33 and 6.66 %. C. The percentage of household income spent on energy services over the last 10 years is between 6.66 and 9.99 %. D. The percentage of household income spent on energy services over the last 10 years is equal or more than 9.99 %.	A: 1.00 B: 0.66 C: 0.33 D: 0.00
Regional conditions	1.1 Regional economic independency from the CCI sector	A. The CCI sector has been closed or the employment contribution has decreased by 90 % or more. B. The CCI sector is in the process of closing due to a binding policy and its employment contribution has decreased. C. The CCI sector has no binding plans to close but its employment contribution has decreased more than 10 %. D. The CCI sector has no binding plans to close and its employment contribution has not decreased by more than 10 %	A: 1.00 B: 0.80 C: 0.40 D: 0.00
	1.2 Decarbonization of the regional energy system	A. More than 40 % of the regional electricity consumption comes from renewable sources. B. More than 30 % and less than 40 % of the regional electricity consumption comes from renewable energy sources. C. More than 20 % and less than 30 % of the regional electricity consumption comes from renewable energy sources. D. Less than 20 % of the regional electricity consumption comes from renewable energy sources.	A: 1.00 B: 0.80 C: 0.60 D: 0.00
	1.3 Technical feasibility for the CCI sector transformation in the region	A. Low-carbon energy sources are available and have been proven (e.g.. steel industry going from coal to hydrogen).	A: 1.00 B: 0.70 C: 0.30 D: 0.00

(continued on next page)

Table 3 (*continued*)

Dimension	Indicator	Levels and related fs-QCA values	Fuzzy values
		B. More than 2 options are available but have not been explored. C. Less than 2 options are available but have not been explored (e.g.. oil wells with geothermal potential). D. No options are available to explore or not feasible (e.g.. coal mines where geothermal energy cannot be used).	
(Inter)national conditions	2.1 Policy mixes at the national and international level	A. There are binding international or national policies promoting an energy transition that the region has already met. B. There are binding international or national policies promoting an energy transition that the region has to meet eventually. C. There are international or national policies promoting an energy transition but they are not binding for the region. D. There are no international nor national policies promoting an energy transition.	A: 1.00 B: 0.70 C: 0.40 D: 0.00

$$HEX_i = \sum_i^j household\_energy\_demand^j_{NUTS-2,2017} \times energy\_price^j_{NUTS-1,i} \quad (3)$$

$$i = \{2012, 2017, 2022\}, j = \{coal, naturalgas, oil, electricity\}$$

3.3. Data analysis

The data analysis used the fs-QCA method to examine the complex relationships between the four conditions and energy affordability in transitioning CCIRs. The study was conducted using the fs-QCA 4.1 free software made available by the University of California (Ragin and Sean, 2022), which allows for assessing necessary and sufficient conditions and solutions for the outcome of interest. QCA best practices were followed to strive for robustness and transparency: being transparent about the methodological steps to ensure reproducible research, specifically, providing information on the data calibration; being clear about methodological choices like consistency thresholds and selection of conditions; discussing how these choices influence the results, and; a being familiar with the cases, among others (Schneider et al., 2019; Schneider and Wagemann, 2010).

First, data on the four selected conditions for all cases were prepared by converting the qualitative data into fuzzy set membership scores. For this step, each condition was measured with an indicator, as presented in Table 3, and each indicator had between 3 and 4 possible levels. Each level received a fuzzy value ranging from 0 to 1, each with a different meaning. The fuzzy values were assigned according to their qualitative meaning and not to achieve variation among the cases as recommended (Schneider and Wagemann, 2010).

Next, the fs-QCA analysis was performed to identify the conditions associated with the outcome of energy affordability (high as MEAFFO and low as meaffo). The sufficiency and consistency of the prime implicants were then assessed to determine their robustness and relevance. The tied prime implicants found for low affordability are presented in Table 8. All conditions were assumed to be positively associated with high affordability. This directionality was considered in the intermediate solution computation. The results were interpreted using set-theoretic logic, examining the combination of conditions that led to the outcome and the degree of coverage and consistency achieved by the identified configurations (Schneider and Wagemann, 2012). A raw consistency threshold of 0.8 was used as the cut-off point to determine the presence of the outcome. This means that whenever the combination of conditions (row) has a raw consistency equal to or higher than 0.8, MEAFFO gets a score equal to 1, and 0 otherwise. Then, each condition's degree of necessity and sufficiency was identified, and the results were presented using truth tables and logical remainders.

A case-study analysis was performed to validate the fs-QCA results and improve the robustness of QCA results (Kimbrell, 2022). Specifically, solutions for high and low affordability were analyzed in-depth to discuss potential inaccuracies from the QCA approach.

4. Conditions for energy affordability in CCIRs: Fs-QCA and case study results

The fuzzy values for the outcome ranged from 0 to 1, as shown in Tables 3, 4, and Appendix A in more detail. Eleven cases received high energy affordability values (MEAFFO), whereas three received low values (meaffo). Results from the fs-QCA reveal potential synergies and trade-offs between the conditions of the research model are presented in Tables 6-9. None of the conditions proved individually necessary nor sufficient for high or low regional energy affordability (see Tables 7 and 9).

Tables 5 and 7 show the truth tables when the outcome is present and absent, respectively. The rows in the truth tables show the logical remainders, which describe the possible combinations of conditions that are sufficient or not for the outcome. These results present the relationships between the combinations of conditions with assigned cases and the outcome. The combinations of conditions are sorted from the highest to the lowest raw consistency value.

Tables 6 and 8 present the standard analysis with the complex, parsimonious, and intermediate solution terms for the fs-QCA when the outcome is present and absent, respectively. Although the three solutions terms are discussed, more attention can be paid to the intermediate solution because it considers the theoretical framework's assumptions presented in Section 2. The complex solution term shows the combination of conditions, considering the pool of cases. The parsimonious solution shows the minimal combination of conditions after performing a logical minimization (Charles, 1987; Ragin, 2009). Finally, the intermediate solution terms are presented in the lower section of Tables 6 and 7. For this solution, no tied implicants were found. In this framework, a primary assumption is that each condition positively associates with the outcome, as described in the intermediate solution. All tied implicants of Table 8 were kept because they were all considered plausible.

4.1. Interpreting fs-QCA results with qualitative case study validation

According to the complex and intermediate solutions, CCIRs' (low or high) energy affordability does not depend on only one condition but rather on combinations of the four conditions. A case study validation effort was made to understand the nuances of fs-QCA results. An overview of fs-QCA results and case study validation for high and low energy affordability is presented in Table 9 and interpreted in the following subsections.

According to the complex and intermediate solutions presented in

Table 4
Regional cases, fuzzy values of their outcome (MEAFFO) and four conditions (CCIND, DECA, TECHFEA, and INTNATPOL).

Coal and carbon-intensive region	Outcome Household's energy affordability	Level of CCI sector independence (CCIND)	Level of decarbonization (DECA)	Transition's technical feasibility (TECHFEA)	Support from (inter)national policies (INTNATPOL)
	High-energy affordability (MEAFFO)				
Upper Austria (AT)	0.66	0.00	1.00	0.70	0.70
Bali (IDN)	0.66	0.00	0.00	0.70	0.70
Düsseldorf (DE)	1.00	1.00	0.00	0.00	1.00
Baja California (MX)	0.66	0.00	0.60	1.00	0.70
Balearic Islands (BES)	1.00	0.80	0.00	1.00	0.70
Teruel (TES)	0.66	1.00	1.00	0.00	1.00
Sulcis (IT)	1.00	1.00	0.80	1.00	1.00
Lofoten (NO)	0.66	1.00	1.00	1.00	1.00
Upper Silesia (PO)	1.00	0.80	0.00	0.70	0.70
Jiu Valley (RO)	0.66	0.80	0.00	0.00	0.00
Alberta (CA)	1.00	0.00	0.00	0.70	0.70
	Low-energy affordability (meaffo)				
Megalopolis (GR)	0.33	0.80	0.80	0.30	0.70
Greenland (GREE)	0.33	0.40	1.00	1.00	0.00
Moravian-Silesian (CZ)	0.33	0.80	0.00	0.00	0.70

Table 5
Truth table for the presence of the outcome MEAFFO=f(CCIND, DECA, TECHFEA, INTNATPOL).

CCIND	DECA	TECHFEA	INTNATPOL	MEAFFO	Cases	raw consist.	PRI consist.	SYM consist
1	0	1	1	1	CZ(0.70)DE(1.00)	1.00	1.00	1.00
0	0	1	1	1	GR(0.70)TES (1.00)	0.98	0.97	1.00
0	1	1	1	1	CA(0.70)IDN (0.70)	0.97	0.94	1.00
1	1	1	1	1	BES(0.70)PO(0.70)	0.84	0.77	1.00
1	0	0	1	1	AT(0.70)MX(0.60)	0.83	0.78	0.79
1	1	0	1	0	IT(0.80)NO(1.00)	0.58	0.31	0.49
1	0	0	0	1	RO(0.80)	0.91	0.82	1.00
0	1	1	0	1	GREE(0.60)	0.81	0.00	0.00
0	0	0	0		No cases			
0	1	0	0		No cases			
1	1	0	0		No cases			
0	0	1	0		No cases			
1	0	1	0		No cases			
1	1	1	0		No cases			
0	0	0	1		No cases			
0	1	0	1		No cases			

Table 6, CCIRs' high energy affordability appears to be associated with the technical feasibility of an energy transition and support from (inter) national policy mixes. When present, this configuration was linked with high energy affordability for four upstream regions, Sulcis (IT), Upper Silesia (PO), Lofoten (NO), and Alberta (CA), and four downstream regions, Balearic Islands (BES), Upper Austria (at), Bali (IDN), and Baja California (MX).

The complex and intermediate solution terms shown in Table 8 overlap with two conditions for low energy affordability. These are a low level of independence from the CCI sector and little or no support from (inter)national policies. Moreover, the complex solution also includes a high level of decarbonization and technical feasibility. The model with four conditions only converged for Greenland, one of the three CCIRs assessed with low energy affordability. Megalopolis (GR) and Moravian-Silesian (CZ) were not described by the model and required consistency values.

4.1.1. *Case study validation of high energy affordability: When the CCI sector's transition is technically feasible*

Two CCIRs were selected to dive deeper into the meaning of the fs-QCA results for high energy affordability. In Baja California (MX), the downstream carbon-intensive sectors mainly operate gas and diesel-fired power generation, while in Alberta (CA), oil and gas extraction represent the upstream carbon-intensive sectors. A similarity observed between these North American regions is their relationship with the United States' natural gas market. While Baja California (MX) imports natural gas from the United States, the latter is Alberta's (CA) most important trading partner, importing a large portion of its natural gas.

The technical feasibility of the CCI sector's low-carbon energy transition (1.3 TECHFEA) was associated with high energy affordability in transitioning CCIRs. This condition indicates that the sector's transition is technically feasible because these regions have one or more clean energy sources available to replace fossil fuels. In the case of Baja California (MX), the technical feasibility is related to the local availability of renewable energy sources to replace fossil fuel (natural gas and diesel) power generation. In this region, renewable energy-based power generation has a median value of around 27 % of the total regional power generation from 2012 to 2020 (own calculation based on official data), with geothermal energy the most utilized renewable energy source (Miranda-Herrera, 2015; SENER, 2018). Renewable energy development in Baja California (MX) is market competitive, especially since the levelized cost of electricity (LCOE) of geothermal and wind energy has proven competitive compared to highly efficient gas-fired power plants (Hiriart and Andaluz, 2000; Muñoz-Andrade et al., 2019). However, the region's share of renewables decreased over the last decade despite its widespread but underutilized energy sources

Table 6
Standard Analysis of the fs-QCA: Complex, parsimonious, and intermediate solutions for high energy affordability (MEAFFO).

MEAFFO=f(CCIND, DECA, TECHFEA, INTNATPOL)	Raw coverage	Unique coverage	Consistency	Cases with greater than 0.50 membership in term
Complex solution				
TECHFEA*INTNATPOL	0.61	0.43	0.93	IT (1.00), NO (1.00), PO (0.70), CA (0.70), BES (0.70),IND (0.70), MX (0.70), AT (0.70)
CCIND*∼DECA*∼TECHFEA	0.25	0.20	0.80	DE (1.00), CZ (0.80), RO (0.80)
∼CCIND*DECA*TECHFEA	0.18	0.03	0.85	AT (0.70), GREE (0.60), MX (0.60)
frequency cutoff: 1consistency cutoff: 0.81				
solution coverage: 0.84solution consistency: 0.86				
Parsimonious solution				
∼DECA	0.65	0.26	0.83	CZ (1.00), DE (1.00), PO (1.00), RO (1.00), CA (1.00), BES (1.00), IDN (1.00)
TECHFEA	0.67	0.28	0.82	IT (1.00), NO (1.00), PO (0.70), CA (0.70), BES (1.00),GREE (1.00), MX (1.00), AT (0.70), IND (0.70)
frequency cutoff: 1consistency cutoff: 0.81				
solution coverage: 0.93solution consistency: 0.77				
Intermediate solution				
Assumptions:CCIND (present)DECA (present)TECHFEA (present)INTNATPOL (present)				
CCIND*∼DECA	0.40	0.22	0.87	DE (1.0), CZ (0.80), PO (0.80), RO (0.80), BES (0.80)
DECA*TECHFEA	0.34	0.03	0.76	NO (1.00), IT (0.80), GREE (1.00), AT (0.70), MX (0.60)
TECHFEA*INTNATPOL	0.61	0.16	0.93	IT (1.00), NO (1.00), PO (0.70), CA (0.70), BES (0.70),IND (0.70), AT (0.70), MX (0.70)
frequency cutoff: 1consistency cutoff: 0.81				
solution coverage: 0.86solution consistency: 0.83				

Table 7
Truth table for lower energy affordability: meaffo = f(CCIND, DECA, TECHFEA, INTNATPOL).

CCIND	DECA	TECHFEA	INTNATPOL	number	cases	raw consist.	PRI consist.	SYM consist
1	1	0	1	2	CZ(0.70)DE(1.0)	0.59	0.33	0.52
0	1	1	1	2	GR(0.70)TES(1.0)	0.59	0.00	0.00
1	0	0	1	2	CA(0.70)IDN(0.70)	0.40	0.20	0.21
0	0	1	1	2	BES(0.70)PO(0.70)	0.37	0.00	0.00
1	1	1	1	2	AT(0.70)MX(0.60)	0.31	0.00	0.00
1	0	1	1	2	IT(0.80)NO(1.00)	0.11	0.00	0.00
0	1	1	0	1	RO(0.80)	1.00	1.00	1.00
1	0	0	0	1	GREE(0.60)	0.53	0.00	0.00
0	0	0	0	0	No cases			
0	1	0	0	0	No cases			
1	1	0	0	0	No cases			
0	0	1	0	0	No cases			
1	0	1	0	0	No cases			
1	1	1	0	0	No cases			
0	0	0	1	0	No cases			
0	1	0	1	0	No cases			

(Muñoz-Andrade et al., 2019). The consequences of relying on natural gas were perceived in 2022, when the Electricity Federal Commission (CFE), the Mexican state-owned electric utility, and TSO, reported a 19 % increase in energy costs due to natural gas price fluctuations (Alvarez, 2023; IEA, 2020).

In the case of Alberta (CA), technical feasibility is related to the potential to repurpose Alberta's idle oil and gas wells with geothermal energy for heating (Ali, 2019). However, this technology is in the early research phase. Currently, the region lacks economic feasibility as well as any political and policy support whilst lacking an immediate transitioning strategy for the CCI sector (Ali, 2019). According to the province's electric system operator, the LCOE of renewables in Alberta (CA) is reported to be significantly lower than coal and natural gas (AESO, 2021). Yet, capital investments in oil and gas continue, amounting to CAD 18 billion alone in 2021 (GOA, 2023a).

The second condition of the solution term is 1.4 INTNATPOL, meaning that national or international policy mixes supporting the regional energy transition positively impact energy affordability. In Mexico, national policies on energy poverty focus on achieving households' energy efficiency by supplying energy-efficient electrical appliances and lighting (de Buen et al., 2022). Although this measure is considered to have effectively decreased households' energy consumption (IEA, 2021), it may overlook the needs of households with extra low consumption levels (González-Eguino, 2015). The governmental effort that has greatly impacted household energy affordability is the national subsidy on the electricity tariffs for the residential sector, with a yearly median spending of €4562 MEUR in the last ten years (CFE, 2023). However, several empirical studies have revealed that electricity subsidies fail to reach households suffering from higher rates of energy poverty, and instead, most of the subsidies are consumed by the wealthiest people (González-Eguino, 2015).

Moreover, the Mexican Federal Commission of Electricity has

Table 8
Standard Analysis of the fs-QCA: Complex, parsimonious, and intermediate solutions for low energy affordability.

~MEAFFO=f(CCIND, DECA, TECHFEA, INTNATPOL)	Raw coverage	Unique coverage	Consistency	Cases with greater than 0.5 membership in term
Complex solution				
~CCIND*DECA*TECHFEA*~INTNATPOL	0.35	0.35	1.00	GREE (0.60)
frequency cutoff: 1.00consistency cutoff: 1.00				
solution coverage: 0.35solution consistency: 1.00				
Parsimonious solution				
~CCIND*~INTNATPOL	0.52	0.10	0.75	GREE (0.60)
DECA*~INTNATPOL	0.39	0.00	0.83	GREE (1.00)
TECHFEA*~INTNATPOL	0.46	0.00	0.60	GREE (1.00)
frequency cutoff: 1.00consistency cutoff: 1.00				
solution coverage: 0.56solution consistency: 0.65				
Tied implicants:				
~CCIND~INTNATPOL				
DECA~INTNATPOL				
TECHFEA~INTNATPOL				
Intermediate solution				
Assumptions:~CCIND (absent)~DECA (absent)~TECHFEA (absent)~INTNATPOL (absent)				
~CCIND*~INTNATPOL	0.52	0.52	0.75	GREE (0.60)
frequency cutoff: 1.00consistency cutoff: 1.00				
solution coverage: 0.52solution consistency: 0.75				

reported these subsidies as economically unsustainable over the last decades (Komives et al., 2009; World Bank, 2005). Generally, Mexican energy transition policies at the national level failed to address energy poverty directly (García-Ochoa et al., 2016), even more so at the regional level. The Baja California State's Energy Commission has initiated a project to address energy poverty in the state in collaboration with research institutions (DTJ, R., 2022; García-Ochoa et al., 2022).

In Canada, national policies do not formally recognize energy poverty as an issue, even though between 6 % and 19 % of households live in energy poverty (Riva et al., 2021). Energy poverty awareness also varies between Canadian provinces. As a relatively wealthy province and large energy producer, energy poverty in Alberta was more seriously acknowledged in 2015 after the report – "Energy Poverty: An Agenda for Alberta" – was published. According to 2016 figures, one in seven families was considered energy-poor; however, the poorest households spent 14.9 % of their disposable household income on energy costs, which was 8.1 times more than the wealthiest households (Boyd and Corbett, 2018).

Another aspect of policy mixes at the national and international level concerns the risk they pose of reinforcing carbon lock-ins when no transition policy targets the CCI sector particularly. While climate policies aim for decarbonization goals have been enacted in Canada and Mexico, these policies do not necessarily lead to the sustainable transformation of the CCI sectors. In Mexico, the Energy Transition Law aims for 35 % and 50 % of clean electricity generation by 2024 and 2050, respectively, whereas the General Law on Climate Change aims for a 50 % GHG emission reduction by 2050 compared to the year 2000 (DOF, 2020, 2015). Although the goals can be ambitious, these policy mixes have not helped to overcome structural lock-ins that reinforce Baja California's (MX) dependency on natural gas for power generation. Alberta (CA) has policies to reduce carbon emissions for large industries and capping emissions in the oil sands, mainly through increased efficiency in production processes and carbon capture and storage (GOA, 2023a). However, these GHG emission reduction policies have not placed sufficient pressure to transform CCI sectors, so they fail to ensure the energy sector's decarbonization. Such an absence of CCI sector policies is also observed in the steel and iron industry in Upper Austria (Maier et al., 2024).

Our measure of energy affordability reflects the situation of an average household. According to the fuzzy value calibration described in Table 3, all cases with average household spending of less than 6.6 % of their income on heating and electricity were classified as experiencing high energy affordability. Since the outcome indicator (see equations 1–3) was based on the energy expenditure of an average household in the region, the results do not describe households experiencing more energy poverty. In the case of Baja California (MX), high energy affordability does not correspond to the sub-sections of the population spending significantly more due to higher energy tariffs or difficult access to energy services. In Mexicali, the capital city of Baja California (MX), around 35 % of the household income was spent on electricity only for air conditioning due to temperatures surpassing 50 °C in summer (Baylon, 2022).

Furthermore, a 2020 survey revealed that 26,000 people lived in energy poverty in Baja California (MX) because they lacked access to electricity, mainly due to irregular land permissions (García-Ochoa et al., 2022). In the case of Alberta (CA), energy poverty was reported as a major issue for 14 % of households (Boyd and Corbett, 2018) and may even worsen due to high unemployment of 5.8 % (GOA, 2023b). Among the previously described reasons are expensive energy services, low household income, high unemployment, and thermal-inefficient homes (Boyd and Corbett, 2018).

Although the CCI sector contributes to the region's economy, it may worsen energy poverty. The region's economic dependency on a still profitable CCI sector may offer jobs in the region, such as in the case of Alberta (CA). Alberta employed 138,000 people in its upstream energy sector (Statistics Canada, 2022), which remains lower than its peak in 2014. The province's oil and gas sectors are of key economic importance, contributing 72 % of the revenues from non-renewable resources in 2021–2022 (GOA, 2023a). Notwithstanding its contribution to the region's wealth and household income, the oil sands sector may also contribute to energy poverty in Alberta (CA), as most energy poverty in Canada and Alberta is not found among low-income households. A study revealed that 7.5 % of low-income and 13.4 % of non-low-income households are in energy poverty, based on how many households struggle to pay their energy bills (Empower Me, 2018). For this reason, the present study's fs-QCA study's measure of energy affordability in Alberta must be cautiously interpreted to consider contextual conditions in the province, as these results may be misused to counteract local efforts to raise awareness of energy poverty experienced by a growing number of households.

Table 9
Comparison of findings from the fs-QCA and case study approach.

Coal and carbon-intensive region	fs-QCA solution terms	Qualitative case study validation
High energy affordability (MEAFFO)		
Four upstream regions:Sulcis (IT)Lofoten (NO)Alberta (CA), andUpper Silesia (PO). Four downstream regions: Balearic Islands (BES)Upper Austria (AT)Baja California (MX) and Bali (IDN).	The complex and intermediate solutions agree on the presence of two conditions for high energy affordability:1.3 Technical feasibility of the CCI's sector transition (TECHFEA).1.4 Support from the (inter)national policy mixes to the regional transition (INTNATPOL).	Case study validation reveals 1.3 Technical feasibility as the most relevant condition for high energy affordability in downstream regions. The example of fossil-fuel-based power generation in Baja California, Mexico: High energy affordability in Baja California can be due to a highly subsidized energy bill. There are top-down, multi-level governance efforts for the transition. However, the national transition agenda is unclear and binding at the regional level. Yet, renewable energy sources are available in the region, and their prices are competitive. They could help avoid or loosen natural gas lock-ins. The chosen average household energy affordability indicator did not accurately reflect the high energy poverty levels previously reported in Alberta. Alternatives to transition the oil and gas sector in Alberta, Canada, exist but are not yet commercially viable or competitive. Decarbonization policies in Canada fall short of driving a sustainable transition in the oil and gas sector, and they do not cover household affordability issues.
Low energy affordability (meaffo)		
One downstream region: Greenland (GREE).	The complex (with higher consistency) and intermediate solution terms agree on two conditions for low energy affordability:1.1 A low level of CCI sector independence (~CCIND).1.4 Little support from the national and international policies for the energy transition of Greenland (~INTNATPOL). The complex solution also includes:1.2 A high level of decarbonization (DECA).1.3 Technical feasibility for the transition (TECHFEA).	Case study validation reveals lack of condition 1.4 Support from international policies as Greenland's most relevant condition for low energy affordability. The CCI sector in Greenland is based on fossil-fuel imports for heating and electricity generation. Greenland is highly dependent on the CCI sector. High energy import prices are reflected in energy bills. International policies have promoted oil exploration, while the local government wants to follow social and sustainable development.

4.1.2. *Case study validation of low-energy affordability: International policies hindering CCIRs energy transitions*

To discuss the configuration of conditions for low energy affordability (meaffo), the case Greenland (GREE) was selected for further elaboration because it was the only one covered by the standard analysis (see Table 8). The fs-QCA results partially describe the relationship between conditions and low energy affordability, for which our outcome formula calculated 7.3 % of household income spent on energy services. The complex and intermediate solution terms agree on two conditions for low energy affordability: a low level of CCI sector independence (~CCIND) and little support from national and international policies for the energy transition of Greenland (~INTNATPOL). Additionally, the complex solution contains a high level of decarbonization and technical feasibility for the transition.

The CCI sector in Greenland (GREE) has declined over the last decade (2012–2022); however, its participation in the energy system remains significant. The CCI sector in Greenland (GREE) imports diesel oil for backup heating and power generation, especially in the areas with no hydroelectric energy projects (Pantaleo et al., 2022). In 2020, Greenland (GREE) produced 70 % of its energy (electricity and heating) for the public sector's consumption from renewable energy sources, such as hydropower 66 % and waste 4 %, and small-scale wind and solar energy generation (Nukissiorfiit, 2021). Yet, 30 % and 56 % of energy generation for the public and private sector was fossil-fuel-based, with diesel oil as the primary source. Diesel oil is imported from abroad, which the Greenlandic energy utility, Nukissiorfiit, reports as expensive. For this reason, the utility is looking for a replacement with local renewable energy sources (Ibid). The high diesel costs threaten the ability of communities in Northern Greenland to afford food and housing (Pantaleo et al., 2022). In general, the energy system's dependence on diesel negatively impacts the energy affordability of Greenlandic people.

The last condition for Greenland's energy affordability is the alignment of (inter)national policy mixes and the regional transition strategy. Greenland (GREE) presents one of the few cases where the energy policy mixes at the international level do not support the regional-level energy transitions. Instead, international policies and global trends promoted oil exploration on the island for exportation purposes (Olsen and Hansen, 2014). This opposes the Government of Greenland's efforts to become economically independent and achieve social and sustainable development (Martinez-Reyes et al., 2022). In 2021, the new Government of Greenland banned oil drilling for environmental and financial reasons (DW, 2021). Here, international policy mixes counteract support for regional transition; in fact, they hinder the development of local renewable energy projects and indirectly negatively impact energy pricing.

5. Discussion and conclusion: The impact of regional energy transitions on household affordability

This study analyzed the relationship between regional, national, and international conditions and energy affordability of 14 CCIRs in Western and majority world countries. Overall, the analysis confirmed the influence of the four selected conditions on affordability. Contextual differences between the regions may be why none of the four conditions resulted as necessary or sufficient for energy affordability. Yet, the fs-QCA model converged, so it could reveal the combinations of conditions that are associated with energy affordability. Furthermore, our cases confirmed the theoretical expectations for energy affordability described in Section 2. An important finding of this study is the distinction of conditions for regions phasing-out or transitioning the CCI sector.

This study shows the importance of certain regional conditions, which had not been included in previous energy affordability studies. The conditions associated with energy affordability for upstream and downstream CCI regions were the regional sector's technical feasibility to transition and the alignment with the (inter)national policies. The presence of a high degree of a region's independence from the CCI sector was observed when there was no technical feasibility to transition. These regional conditions are key to understanding energy affordability in energy regions, especially in CCIRs.

Additionally, a sector's technical feasibility to transition appears to be associated with affordability in transitioning CCIRs. These results differ with most regions phasing-out coal, except for regions like Sulcis and Upper Silesia, which consider CCS or CCT for the sector's transition. The terms phasing-out (with no technical feasibility) and transitioning CCIRs (with technical feasibility) can be employed to distinguish between these regions. One could conclude that if a carbon-intensive sector does not have alternatives to decarbonize, it might risk a decline if a low-carbon regional transition strategy is adopted. Furthermore, upstream regions like oil sands and downstream regions like fossil-fuel-fired power sectors can be part of a slow-paced energy transition, also referred to as an on-stream transition pathway (Lieu et al., 2020), since there is no evidence of a transformative policy for the CCI sectors in these regions.

Regional and (inter)national conditions were always combined in all fs-QCA results, highlighting a multi-level governance nature of energy regions. This suggests that it may be necessary for policymakers to synchronize an energy transition strategy with regional economic development plans to avoid negative socioeconomic impacts during the CCI sector's transition or phase-out. This is in line with results from a study by Kern & Rogge (2016) who found that it is important to align sectoral plans with (inter)national transition policies. This was also observed in the Greenland region case, where international policies were found to support oil exploration, posing a carbon lock-in risk in the region. It is important to note that transition policies may negatively impact affordability in the long term if they overlook regional challenges like carbon lock-ins or energy poverty, as also concluded in a previous study (Primc and Slabe-Erker, 2020). Therefore, it should be considered that national and regional levels of government coordinate their strategies to combat energy poverty and avoid path dependencies. This applies to both the EU and non-EU regional cases studied (European Commission, 2020).

5.1. Limitations and suggestions for future research

The indicator measuring an average household's energy affordability can indicate energy poverty when most of the population is affected, or a section of the population is severely affected, but not when there is a high level of economic inequality. Thus, future studies on energy poverty should consider not only affordability but also accessibility and household-level conditions (González-Eguino, 2015). For a more comprehensive analysis of just transitions, it is suggested that dimensions like recognition, procedural, and distributional justice be included. As the data required to capture energy poverty and justice are typically quantitative and qualitative, adopting a fs-QCA research approach with expert validation can be handy, as shown in this study.

Future studies can analyze other conditions of carbon-intensive industries. For instance, fossil fuel subsidies, often indirectly funded by taxpayers, were not included as the energy prices for electricity and heating available in public databases like Eurostat do not consider such subsidies. Yet, it is worth analyzing the impact of these subsidies in countries with high energy subsidies, like Indonesia and Mexico (Komives et al., 2009; Maulidia et al., 2019). Additionally, different factors need to be considered for relatively wealthy regions, like the impact of high unemployment and the costs and quality of housing stocks, which impact energy affordability differently across income groups (Boyd and Corbett, 2018).

Access to comprehensive databases at the regional level for case studies from different parts of the world is an important constraint. Another way to achieve variability may be to compare regions within the same country with high data availability. An assumption in QCA is that the conditions must be identified before the analysis, or the QCA needs to be run iteratively. An approach to offset this limitation is to apply fs-QCA ex-ante and ex-post to a (limited) number of case studies where verification can still be feasible, with the possibility for adjustment during the study.

The major policy implication of these findings lies in the need for energy poverty alleviation policies to consider the contextual differences between phasing-out and transitioning CCIRs. The EU Just Transition Fund offers the same resources to all CCIRs indistinctively. This programme encourages CCIRs to tackle energy poverty using bottom-up strategies (territorial just transition plan) that each region oversees (Commission, 2021b; Oj l., 2021). In return, some CCIRs may not easily embark on a just transition pathway because their challenges go beyond what a regional transition strategy or program may attain. This may be due to the availability of low-carbon energy sources and technologies, market rules, global energy prices, or (inter)national policies. Therefore, regional strategies should be supported by a multi-level governance and cross-sectoral economic development approach, not only through funds. Furthermore, if the Just Transition Mechanism enables cross-learning between similar CCIRs, their strategies might become more effective. Besides the industry similarity, the temporality of each region's transition is also essential to consider when clustering regions, as the challenges they face may be related to the transition stage.

CRediT authorship contribution statement

Amanda Martinez-Reyes: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jenny Lieu:** Writing – original draft, Validation, Supervision, Investigation, Funding acquisition, Conceptualization. **Nihit Goyal:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Diana Mangalagiu:** Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Funding acquisition. **Thomas Hoppe:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Martínez-Reyes Amanda declares that this paper was funded by the European Union's Horizon 2020 research innovation programme TIPPING+ "Enabling Positive Tipping Points towards clean-energy transitions in Coal and Carbon Intensive Regions" under the grant agreement No. 884565 and the NEOMA Business School's funding "Areas of Excellence The World We Want: Inclusion, Equality and Diversity".

Data availability

Data will be made available on request.

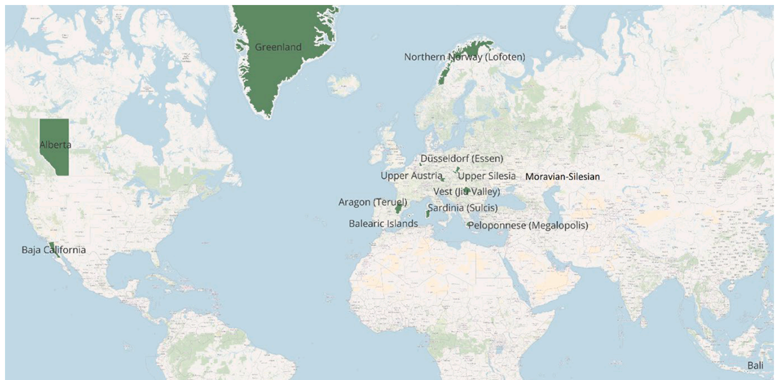
Acknowledgments

The authors extend sincere gratitude to the regional case study partners for their invaluable input and support, which provided the data and data validation of this research article: Raphaela Maier, Bohumil Frantál, Francesc Cots, Serafeim Michas, Cynthia Ismail, Brigt Dale, Joanna Mazurkiewicz, Jan Frankowski, Arpad Todor, Franziska Mey, Anne Merrild Hansen, Mauro Sarrica, Andreas Türk, Stanislav Martinát, Jindřich Frajer, Lucia Brisudová, Cristina Costa, Gerard Codina, Jérémie Fosse, Zois Katiforis, Nikos Kleanthis, Alexandros Flamos, J. David Tàbara, Takeshi Takama, David Saurí Fulvio Biddau, Anna G. Sveinsdóttir, Jakub Sokołowski, Andrei Țăranu, Robert Udrea, Johan Lilliestam, Regine-Ellen Møller, Chelsey Greene, and Luis D. Virla. The authors are also grateful for the 150 + stakeholders involved in our research who provided us with valuable insights and knowledge. This research would not be possible without their collaboration. The authors also acknowledge the internal reviewers (Fulvio Biddau and Jan Frankowski) for their critical feedback that helped strengthen this paper.

These collective efforts have played a pivotal role in ensuring the quality and significance of this research for the journal.

Appendix A. Raw case study data

The calculation of the fuzzy values from raw data can be found in the following repository: https://github.com/Amininor/fs-QCA-data-validation-and-sources.git.



.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2024.102936.

References

Ali, B., 2019. Sustainability Assessment of Power Generation from an Abandoned Oil and Gas Well in Alberta, Canada. Journal of Energy and Power Technology 1, 1–22. https://doi.org/10.21926/jept.1903002.

Banerjee, A., Prehoda, E., Sidortsov, R., Schelly, C., Banerjee, A., Prehoda, E., Sidortsov, R., Schelly, C., 2017. Renewable, ethical? Assessing the energy justice potential of renewable electricity. AIMSE 5, 768–797. https://doi.org/10.3934/energy.2017.5.768.

Baylon, K., 2022. Mexicalenses destinan hasta 35% de salario para pagar luz. El imparcial.

Boardman, B., 1991. Fuel Poverty: From Cold Homes to Affordable Warmth, illustrated edition. ed. UNKNO, London ; New York.

Bonatz, N., Guo, R., Wu, W., Liu, L., 2019. A comparative study of the interlinkages between energy poverty and low carbon development in China and Germany by developing an energy poverty index. Energ. Buildings 183, 817–831. https://doi.org/10.1016/j.enbuild.2018.09.042.

Boschma, R., Coenen, L., Frenken, K., Truffer, B., 2017. Towards a theory of regional diversification: combining insights from Evolutionary Economic Geography and Transition Studies. Reg. Stud. 51, 31–45. https://doi.org/10.1080/00343404.2016.1258460.

Bouzarovski, S., Petrova, S., 2015. A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary. Energy Res. Soc. Sci. 10, 31–40. https://doi.org/10.1016/j.erss.2015.06.007.

Bouzarovski, S., Petrova, S., Sarlamanov, R., 2012. Energy poverty policies in the EU: A critical perspective. Energy Policy, Special Section: Fuel Poverty Comes of Age. Commemorating 21 Years of Research and Policy 49, 76–82. https://doi.org/10.1016/j.enpol.2012.01.033.

Bouzarovski, S., Simcock, N., 2017. Spatializing energy justice. Energy Policy 107, 640–648. https://doi.org/10.1016/j.enpol.2017.03.064.

Bouzarovski, S., Tirado Herrero, S., 2017. Geographies of injustice: the socio-spatial determinants of energy poverty in Poland, the Czech Republic and Hungary. Post-Communist Econ. 29, 27–50. https://doi.org/10.1080/14631377.2016.1242257.

Boyd, R., Corbett, H., 2018. An energy poverty strategy for Alberta. Energy poverty, All one sky foundation, Calgary, AB, Canada.

CFE, 2023. CFE reportes financieros [WWW Document]. Comision federal de electricidad. URL https://www.cfe.mx/finanzas/reportes-financieros/pages/reportes-anuales.aspx (accessed 6.29.23).

Cha, J.M., Wander, M., Pastor, M., 2020. Environmental Justice, Just Transition, and a Low-Carbon Future for California. Envtl. l. Rep. 50, 10216.

Charles, R., 1987. The comparative method: Moving beyond qualitative and quantitative strategies. University of California Press.

Che, X., Zhu, B., Wang, P., 2021. Assessing global energy poverty: An integrated approach. Energy Policy 149. https://doi.org/10.1016/j.enpol.2020.112099.

Commission, E., 2018. Platform on Coal and Carbon-Intensive Regions: Terms of Reference. Coal Regions in Transition Platform, European Commission.

Commission, E., 2021b. The territorial just transition plans (Policy report). Commission staff working document, European Commision, Brussels.

European Commission, 2020. Commission Recommendation on energy poverty, OJ L.

European Commission, 2021 accessed 6.12.23. https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes/just-transition-fund_en.

de Buen, O., Morales, N., Navarrete, J.I., 2022. Servicios energéticos, pobreza energética y eficiencia energética: una perspectiva desde México (Policy report. Cuadernos De La CONUEE. Comision Nacional Para El Uso Efficiencte De La Energia. Secretaria De Energia No. 8).

del Guayo, Í., Cuesta, Á., 2022. Towards a just energy transition: a critical analysis of the existing policies and regulations in Europe. The Journal of World Energy Law & Business 15, 212–222. https://doi.org/10.1093/jwelb/jwac010.

Dof, 2015. Ley general de cambio climatico. Diario Oficial de la Federacion, Mexico City, Mexico.

Dof, 2020. Ley de transicion energetica. Diario Oficial de la Federacion, Mexico City, Mexico.

Dtj, r., 2022. Implementa CEE proyecto para erradicar la pobreza energética en el Estado. accessed 7.2.23 Diario Tijuana. https://diariotijuana.info/2022/05/implementa-cee-proyecto-para-erradicar-la-pobreza-energetica-en-el-estado.

Dubois, U., Meier, H., 2016. Energy affordability and energy inequality in Europe: Implications for policymaking. Energy Research & Social Science, Energy Demand for Mobility and Domestic Life: New Insights from Energy Justice 18, 21–35. https://doi.org/10.1016/j.erss.2016.04.015.

DW, 2021. Greenland stops oil and gas exploration. dw.com.

Eca, 2022. EU support to coal regions: Limited focus on socioeconomic and energy transition (Special report. EU Support to Coal Regions No. 22).

Eu,, 2022. REPowerEU: Affordable, secure and sustainable energy for Europe [WWW Document]. accessed 6.9.24 European Commission. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en.

Eurostat, E., 2020. Imports of natural gas [WWW Document]. accessed 7.10.23 Energy Trade. https://ec.europa.eu/eurostat/cache/infographs/energy_trade/entrade.html.

Eurostat, 2023. Energy market indicator [WWW Document]. Energy statistics. URL https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_market/default/table?lang=en (accessed 7.10.23).

Florini, A., 2013. The Coming Democracy: New Rules For Running A New World. Island Press.

Florini, A., Sovacool, B.K., 2009. Who governs energy? The challenges facing global energy governance. Energy Policy 37, 5239–5248. https://doi.org/10.1016/j.enpol.2009.07.039.

Furszyfer Del Rio, J., Furszyfer Del Rio, D.D., Sovacool, B.K., Griffiths, S., 2023. The demographics of energy and mobility poverty: Assessing equity and justice in Ireland, Mexico, and the United Arab Emirates. Glob. Environ. Chang. 81, 102703. https://doi.org/10.1016/j.gloenvcha.2023.102703.

García-Ochoa, R., Graizbord, B., García-Ochoa, R., Graizbord, B., 2016. Caracterización espacial de la pobreza energética en México. Un análisis a escala subnacional. Economía, Sociedad y Territorio 16, 289–337.

García-Ochoa, R., Graizbord, B., Campa Madrid, A.K., Romero Gamboa, M.P., Cordero, G., Esparza, L., Aguillon, C., 2022. Living without electricity in Baja California. University of California San Diego, La Jolla, California, Institute of the Americas.
Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Research Policy, NELSON + WINTER + 20 31, 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8.
Geels, F.W., 2019. Sociotechnical transitions to sustainability: a review of criticisms and elaborations of the Multi-Level Perspective. Current Opinion in Environmental Sustainability, Open Issue 2019 (39), 187–201. https://doi.org/10.1016/j.cosust.2019.06.009.
Goa, 2023a. Oil sands facts and statistics (Governmental report). Government of Alberta, Alberta, Canada.
GOA, 2023b. Alberta Labour Market Review: 2021 - 2022 annual review. (Governmental report), Jobs, Economy and Northern Development. Government of Alberta, Alberta, Canada.
González-Eguino, M., 2015. Energy poverty: An overview. Renew. Sustain. Energy Rev. 47, 377–385. https://doi.org/10.1016/j.rser.2015.03.013.
Government of Canada, 2018. Task Force: Just Transition for Canadian Coal Power Workers and Communities [WWW Document]. Clean technology, innovation and jobs. URL https://www.canada.ca/en/environment-climate-change/services/climate-change/task-force-just-transition.html (accessed 6.12.23).
Heffron, R.J., 2022. Applying energy justice into the energy transition. Renew. Sustain. Energy Rev. 156, 111936. https://doi.org/10.1016/j.rser.2021.111936.
Hermanson, A.-S., 2018. Energy security in a multi-level governance perspective. Mar. Policy 98, 301–308. https://doi.org/10.1016/j.marpol.2018.09.025.
Hiriart, G., Andaluz, J.I., 2000. Strategies and economics of geothermal power development in Mexico, in: Proceedings World Geothermal Congress 2000. Presented at the World geothermal congress, World geothermal congress, Kyushu - Tohoku, Japan, p. 4.
Hoppe, T., Miedema, M., 2020. A Governance Approach to Regional Energy Transition: Meaning. Conceptualization and Practice. Sustainability 12, 915. https://doi.org/10.3390/su12030915.
Iea, 2021. Achievements of Energy Efficiency Appliance and Equipment Standards and Labelling Programmes – Analysis. Energy efficient end-use equipment, International Energy Agency.
IEA, 2020. Levelised Cost of Electricity Calculator – Data Tools [WWW Document]. IEA. URL https://www.iea.org/data-and-statistics/data-tools/levelised-cost-of-electricity-calculator (accessed 7.1.23).
IEA, 2023. Data and statistics [WWW Document]. IEA. URL https://www.iea.org/sankey (accessed 7.19.23).
Ipcc, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Inn Press.
Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016. Energy justice: A conceptual review. Energy Res. Soc. Sci. 11, 174–182. https://doi.org/10.1016/j.erss.2015.10.004.
Karlsson, M., Dale, B., 2019. "It belongs to the world." Oil, conservation and futures in the making in Lofoten. Norway. Sage 37, 1452–1470. https://doi.org/10.1177/2399654419835.
Kern, F., Rogge, K.S., 2016. The pace of governed energy transitions: Agency, international dynamics and the global Paris agreement accelerating decarbonisation processes? Energy Res. Soc. Sci. 22, 13–17. https://doi.org/10.1016/j.erss.2016.08.016.
Kessides, I., Miniaci, R., Scarpa, C., Valbonesi, P., 2009. Toward Defining and Measuring the Affordability of Public Utility Services.
Kimbrell, C.M., 2022. Energy policy as a driver of energy poverty? Perhaps not. Energy Sustain. Dev. 71, 568–572. https://doi.org/10.1016/j.esd.2022.11.003.
Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M.S., Nykvist, B., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P., 2019. An agenda for sustainability transitions research: State of the art and future directions. Environ. Innov. Soc. Trans. 31, 1–32. https://doi.org/10.1016/j.eist.2019.01.004.
Komives, K., Johnson, T., Halpern, J., Aburto, J.L., Scott, J., 2009. Residential Electricity Subsidies in Mexico: Exploring Options for Reform and for Enhancing the Impact on the Poor, No. 47107. World Bank, Washington, DC.
LaBelle, M.C., Bucată, R., Stojilovska, A., 2023. Radical energy justice: a Green Deal for Romanian coal miners? J. Environ. Plann. Policy Manage. 25, 142–154. https://doi.org/10.1080/1523908X.2021.1992266.
Lieu, J., Sorman, A.H., Johnson, O.W., Virla, L.D., Resurrección, B.P., 2020. Three sides to every story: Gender perspectives in energy transition pathways in Canada, Kenya and Spain. Energy Res. Soc. Sci. 68, 101550. https://doi.org/10.1016/j.erss.2020.101550.
Maier, R., Gerres, T., Tuerk, A., Mey, F., 2024. Finding tipping points in the global steel sector: A comparison of companies in Australia, Austria, South Korea and the USA. Global Environmental Change 86, 102846. https://doi.org/10.1016/j.gloenvcha.2024.102846.
Malizia, E.E., Ke, S., 1993. The Influence of Economic Diversity on Unemployment and Stability*. J. Reg. Sci. 33, 221–235. https://doi.org/10.1111/j.1467-9787.1993.tb00222.x.
Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: An emerging field of research and its prospects. Research Policy, Special Section on Sustainability Transitions 41, 955–967. https://doi.org/10.1016/j.respol.2012.02.013.
Martinez-Reyes, A., Lieu, J., Veland, S., Frantal, B., Maier, R., Biddau, F., Mey, F., 2021. Deliverable 5.1: Literature review advancing the state of the art on the characterisation of social-ecological regional energy systems, Work package 5 deliverables. H2020 Tipping plus project, Delft, Netherlands.
Martinez-Reyes, A., Chhetri, A., Lieu, J., 2022. Deliverable 5.2: Case study findings (Deliverable No. 5.2), Work package 5 deliverables. H2020 Tipping plus project, Delft, Netherlands.
Martiskainen, M., Jenkins, K.E.H., Bouzarovski, S., Hopkins, D., Mattioli, G., Lacey-Barnacle, M., 2021. A Spatial Whole Systems Justice Approach to Sustainability Transitions. Environmental Innovation and Societal Transitions, Celebrating a Decade of EIST: What's next for Transition Studies? 41, 110–112. https://doi.org/10.1016/j.eist.2021.10.030.
Marx, A., 2010. Crisp-set qualitative comparative analysis (csQCA) and model specification: Benchmarks for future csQCA applications. International Journal of Multiple Research Approaches 4, 138–158. https://doi.org/10.5172/mra.2010.4.2.138.
Maulidia, M., Dargusch, P., Ashworth, P., Ardiansyah, F., 2019. Rethinking renewable energy targets and electricity sector reform in Indonesia: A private sector perspective. Renew. Sustain. Energy Rev. 101, 231–247. https://doi.org/10.1016/j.rser.2018.11.005.
McCauley, D., Heffron, R.J., Jenkins, S.K., 2013. Advancing energy justice: the triumvirate of tenets. International Energy Law Review, Sweet and Maxwell.
McCauley, D., Heffron, R., 2018. Just transition: Integrating climate, energy and environmental justice. Energy Policy 119, 1–7. https://doi.org/10.1016/j.enpol.2018.04.014.
McCauley, D., Ramasar, V., Heffron, R.J., Sovacool, B.K., Mebratu, D., Mundaca, L., 2019. Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research. Appl. Energy 233–234, 916–921. https://doi.org/10.1016/j.apenergy.2018.10.005.
Me, E., 2018. Energy Poverty in Alberta. Empower Me, Alberta, Canada.
Mello, P., 2021. Qualitative Comparative Analysis: An Introduction to Research Design and Application.
Miranda-Herrera, C.A., 2015. Geothermal and solar energy in Cerro Prieto, in: Proceedings World Geothermal Congress 2015. Presented at the World geothermal congress, World geothermal congress, Melbourne, Australia, p. 7.
Moore, R., 2012. Definitions of fuel poverty: Implications for policy. Energy Policy, Special Section: Fuel Poverty Comes of Age. Commemorating 21 Years of Research and Policy 49, 19–26. https://doi.org/10.1016/j.enpol.2012.01.057.
Muñoz-Andrade, D., Sweedler, A., Martin, J., Prieto, A., Rounds, K., Gruenwald, T., 2019. Baja California Energy Outlook 2020–2025. University of California San Diego, San Diego, U. S, Institute of the Americas.
Nolden, C., Towers, L., Schamroth Rossade, D., Thomas, P., Speciale, G., Watson, R., 2022. Can liberalised electricity markets deliver on climate change and energy poverty? Evidence from community projects in Great Britain. Local Environ. 27, 1151–1171. https://doi.org/10.1080/13549839.2022.2104829.
Ntaintasis, E., Mirasgedis, S., Tourkolias, C., 2019. Comparing different methodological approaches for measuring energy poverty: Evidence from a survey in the region of Attika, Greece. Energy Policy 125, 160–169. https://doi.org/10.1016/j.enpol.2018.10.048.
Nukissiorfiit, 2021. Annual report. Nukissiorfiit, Nuuk, Greenland.
Nussbaumer, P., Bazilian, M., Modi, V., 2012. Measuring energy poverty: Focusing on what matters. Renew. Sustain. Energy Rev. 16, 231–243. https://doi.org/10.1016/j.rser.2011.07.150.
European Parlament and Council, 2021. Regulation (EU) 2021/1056 of the European Parliament and of the Council of 24 June 2021 establishing the Just Transition Fund, OJ L.
Olsen, A.-S.-H., Hansen, A.M., 2014. Perceptions of public participation in impact assessment: a study of offshore oil exploration in Greenland. Impact Assessment and Project Appraisal 32, 72–80. https://doi.org/10.1080/14615517.2013.872842.
Pagliaro, M., Meneguzzo, F., 2020. Distributed Generation from Renewable Energy Sources: Ending Energy Poverty across the World. Energ. Technol. 8. https://doi.org/10.1002/ente.202000126.
Pantaleo, A., Albert, M.R., Snyder, H.T., Doig, S., Oshima, T., Hagelqvist, N.E., 2022. Modeling a sustainable energy transition in northern Greenland: Qaanaaq case study. Sustainable Energy Technol. Assess. 54, 102774. https://doi.org/10.1016/j.seta.2022.102774.
Pau, S., Contu, G., Rundeddu, V., 2022. From mine industries to a place of culture, tourism, research and higher education: case study of the great mine Serbariu. Journal of Cultural Heritage Management and Sustainable Development Ahead-of-Print. https://doi.org/10.1108/JCHMSD-03-2021-0044.
Pellinger, C., Konetschny, C., Sylla, J., Guminski, A., 2019. Generating energy carrier specific space heating and hot water load profiles at NUTS-3-level in Europe, in: 11th International Energy Conference IEWT 2019. Presented at the International Energy Conference IEWT, Vienna.
Pereira, G., González, A., Ríos, R., 2021. Capturing Multidimensional Energy Poverty in South America: A Comparative Study of Argentina, Brazil, Uruguay, and Paraguay. Frontiers in Sustainable Cities 3. https://doi.org/10.3389/frsc.2021.632009.
Primc, K., Slabe-Erker, R., Majcen, B., 2019a. Constructing energy poverty profiles for an effective energy policy. Energy Policy 128, 727–734. https://doi.org/10.1016/j.enpol.2019.01.059.
Primc, K., Slabe-Erker, R., Majcen, B., 2019b. Energy poverty: A macrolevel perspective. Sustain. Dev. 27, 982–989. https://doi.org/10.1002/sd.1999.

Primc, K., Slabe-Erker, R., 2020. Social policy or energy policy? Time to reconsider energy poverty policies. Energy Sustain. Dev. 55, 32–36. https://doi.org/10.1016/j.esd.2020.01.001.

Quinn Patton, M., 2014. Introduction to Qualitative Inquiry Frameworks, in: Qualitative Research & Evaluation Methods: Integrating Theory and PracticeSAGE Publications Inc. SAGE Publications.

Rademaekers, K., Yearwood, J., Ferreira, A., Pye, S., Hamilton, I., Agnolucci, P., Grover, D., Karásek, J., Anisimova, N., 2016. Selecting indicators to measure energy poverty, Energy poverty: assessment of the impact of the crisis and review of existing and possible new measures in the member states. European Commission, Rotterdam, Netherlands.

Ragin, C.C., 1987. The comparative method : moving beyond qualitative and quantitative strategies. University of California Press, Berkeley.

Ragin, C.C., 2009. Qualitative Comparative Analysis using Fuzzy Sets (fsQCA). In: Configurational Comparative Methods: Qualitative Comparative Analysis (QCA) and Related Techniques. SAGE Publications, Inc. https://doi.org/10.4135/9781452226569.

Ragin, C.C., 2023. Analytic Induction for Social Research, 1st ed. University of California Press, California.

Ragin, C.C., Sean, D., 2022. Fuzzy-Set/Qualitative Comparative Analysis 4.0.

Ramos, C., Alvargonzález, M., Moreno, B., 2022. Study of energy poverty in the European Union: the effect of distributed generation. Energy Sources Part B 17. https://doi.org/10.1080/15567249.2021.2018525.

Riva, M., Kingunza Makasi, S., Dufresne, P., O'Sullivan, K., Toth, M., 2021. Energy poverty in Canada: Prevalence, social and spatial distribution, and implications for research and policy. Energy Res. Soc. Sci. 81, 102237. https://doi.org/10.1016/j.erss.2021.102237.

Romero, J.C., Linares, P., López, X., 2018. The policy implications of energy poverty indicators. Energy Policy 115, 98–108. https://doi.org/10.1016/j.enpol.2017.12.054.

Schneider, C., Vis, B., Koivu, K., 2019. Set-Analytic Approaches. Especially Qualitative Comparative Analysis (QCA). https://doi.org/10.2139/ssrn.3333474.

Schneider, C.Q., Wagemann, C., 2010. Standards of Good Practice in Qualitative Comparative Analysis (QCA) and Fuzzy-Sets. Comp. Sociol. 9, 397–418. https://doi.org/10.1163/156913210X12493538729793.

Schneider, C.Q., Wagemann, C., 2012. Set-Theoretic Methods for the Social Sciences: A Guide to Qualitative Comparative Analysis [WWW Document]. Cambridge Core. https://doi.org/10.1017/CBO9781139004244.

Opendata ffe, 2020. Regionalisation of the final energy consumption of the sector private households in Europe. The FfE open data portal. URL https://opendata.ffe.de/ (accessed 6.21.23).

SENER, 2018. Programa de desarrollo del sistema eléctrico nacional 2018-2032. Secretaría de Energía.

Siegel, P.B., Johnson, T.G., Alwang, J., 1995. Regional Economic Diversity and Diversification. Growth Chang. 26, 261–284. https://doi.org/10.1111/j.1468-2257.1995.tb00171.x.

Smith, A., Stirling, A., Berkhout, F., 2005. The governance of sustainable sociotechnical transitions. Res. Policy 34, 1491–1510. https://doi.org/10.1016/j.respol.2005.07.005.

Snell, D., 2018. 'Just transition'? Conceptual challenges meet stark reality in a 'transitioning' coal region in Australia. Globalizations 15, 550–564. https://doi.org/10.1080/14747731.2018.1454679.

Sovacool, B.K., Burke, M., Baker, L., Kotikalapudi, C.K., Wlokas, H., 2017. New frontiers and conceptual frameworks for energy justice. Energy Policy 105, 677–691. https://doi.org/10.1016/j.enpol.2017.03.005.

Sovacool, B.K., Dworkin, M.H., 2015. Energy justice: Conceptual insights and practical applications. Appl. Energy 142, 435–444. https://doi.org/10.1016/j.apenergy.2015.01.002.

Sovacool, B.K., Heffron, R.J., McCauley, D., Goldthau, A., 2016. Energy decisions reframed as justice and ethical concerns. Nat Energy 1, 1–6. https://doi.org/10.1038/nenergy.2016.24.

Villalobos, C., Chávez, C., Uribe, A., 2021. Energy poverty measures and the identification of the energy poor: A comparison between the utilitarian and capability-based approaches in Chile. Energy Policy 152, 112146. https://doi.org/10.1016/j.enpol.2021.112146.

Wang, X., Lo, K., 2021. Just transition: A conceptual review. Energy Res. Soc. Sci. 82, 102291. https://doi.org/10.1016/j.erss.2021.102291.

Ministerie van Algemene Zaken, 2022. Price cap for gas, electricity and district heating: Energy crisis. Energy crisis. URL https://www.government.nl/topics/energy-crisis/cabinet-plans-price-cap-for-gas-and-electricity (accessed 6.13.23).

World Bank, 2005. Mexico - Infrastructure public expenditure review (IPER) (Public Expenditure Review No. 33483). Washington, DC.

Yagi, M., Managi, S., 2023. The spillover effects of rising energy prices following 2022 Russian invasion of Ukraine. Economic Analysis and Policy 77, 680–695. https://doi.org/10.1016/j.eap.2022.12.025.