Qualitative comparative analysis as a method for project studies: the case of energy infrastructure

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Abstract

Empirical research involving projects is an important and common way to advance knowledge in the energy sector, and there are well-established approaches for qualitative analysis of single or few cases (1-10 cases) as well as quantitative analysis of large databases (from 50+ cases). However, the "middle-ground" of analysing 10-50 cases is an unknown territory. Very few approaches exist to deal with numbers of cases that lie in the range of 10 -50. This paper shows how this "middle-ground" can be explored through Qualitative Comparative Analysis (QCA) This is a method that can be applied to energy infrastructure projects (such as construction, operations, and decommissioning of power plants) in order to study causal inference (e.g. factors associated with outcomes). This paper demonstrates the potential of QCA by showing its application on an energy infrastructure phenomenon with an intermediate number of cases, that of nuclear decommissioning projects. These projects are becoming increasingly important to society and have multibillion US dollar budgets. Moreover, their characteristics need to urgently be matched with their project performance in order to avoid even further cost overruns. The application of QCA to 24 European decommissioning projects shows that a combination of characteristics (such as the streamlined governance structure and the presence of a storage facility for radioactive material on site) might be contributing to lower cost overruns. This paper concludes by showing how QCA can be applied to other energy infrastructure phenomena with a similar intermediate number of cases.

Highlights

- There is a gap in knowledge on how to conduct research with 10-50 cases
- This paper shows the applicability of QCA to an intermediate number of cases
- To exemplify this approach, QCA is applied to 24 nuclear decommissioning projects
- Streamlined governance and storage facilities on-site can reduce overruns
- Stable funding for the NDP and storage facilities on-site can reduce overruns

Keywords: Research Method, Qualitative Comparative Analysis, Megaproject, Small-medium size, End-of-Life, Nuclear Decommissioning.

Word Count: 7640

1 Introduction

Most of the empirical research currently undertaken on energy infrastructure phenomena either uses the qualitative 'case-study' analysis of 1 to 10 cases (e.g. [1]–[3]) or the quantitative analysis of databases of 50+ cases (e.g. [4]–[7]).

Case study analysis is extensively used to describe and understand the behaviour of one or more projects and is a very effective method for theory building [8], [9]. As traditionally understood, case study research allows a rigorous and systematic qualitative and highly contextual analysis of a single or a small number of energy projects, [10], [11]. Alternatively, quantitative analysis of databases of 50+ cases allows the application of descriptive statistics (e.g. presenting mean, median, mode and outliers); correlation analysis (to quantify to which degree two variables are associated); and regression analysis (to investigate the relationship of one or more "independent" variables on a "dependent" variable) [12].

Between these two domains, there is a "middle-ground" characterised by researchers dealing with an intermediate number of cases, typically in the range of 10-50. This paper discusses the role of using Qualitative Comparative Analysis (QCA) to explore this "middle-ground" in energy infrastructure phenomena. QCA is particularly useful for small to medium sample sizes [13]. When dealing with 10-50 cases, enough in-depth case knowledge can be retained and used for interpretation which is often diluted or infeasible when attempting to interpret the statistical analysis of large sample sizes. Through QCA, it is also possible to evaluate the influence of both individual independent variables as well as their combinations, linking multiple pathways to an outcome [14]–[16]. So, the main difference between QCA and regression (as well as other statistical tests) is that regression aims to quantify the net independent effect of individual variables on an outcome, examining interactions between variables primarily to establish each one's independent contribution, whereas QCA endeavours to focus on associations between combinations of variables and the outcome, also making explicit the influence of the context and the effect of interactions between variables [17].

1.1 QCA as a bridge between qualitative and quantitative analysis

QCA is an analytical method for case comparison which uses both theory and case knowledge in combination to investigate the relationship between characteristics of a case (both individually and combined) and a performative measure [13].

In QCA, the term "case" is specifically used to represent the unit of analysis (as opposed to"case study research" as described, amongst others, by Yin [10]). In QCA, cases need to be sufficiently understood to operationalise the variables and to interpret and discuss the results of an analysis. QCA bridges the gap between qualitative and quantitative analysis and provides a mechanism to research a small to medium number of cases [15], [16], [18], [19]. QCA combines qualitative and quantitative data and analyses into a single method [20]. QCA uses qualitative information that is "quantified" into numeric data (binary, for crisp-set QCA) and then analysed. This analysis provides information (i.e., indicators that show the relationship between the variables) that researchers need to examine and interpret through their contextural knowledge (i.e., going back to the qualitative data and information gathered during the data collection stage). There are three main different types of QCA analysis: crisp-set QCA, fuzzy-set QCA and multi-value QCA c Crisp-set QCA is particularly useful when all cases analysed exhibit the complete presence or absence of the hypothesized characteristics and outcome. Crisp-set QCA uses a binary coding scheme where the outcome and each condition in the analysis are assigned a value of 0 (non-membership) or 1 (full-membership) based on case knowledge. Where the variables cannot be assigned a dichotomous categorisation, multi-value QCA (where each variable can be assigned one of few discrete values) or fuzzy-set QCA (where each variable can be given a value in a continuous range) can be used. Based on the available data, the ability to categorize variables in a binary manner, and given the exploratory nature of research in this sector using QCA, we used crisp-set QCA. The results of this research will be benchmarked in future using multi-value QCA or fuzzy-set QCA (see section 4).

1.2 Recent and relevant publications about QCA

Until recently, QCA has been applied in a limited fashion [14], [21]. Primarily, QCA has been used in the fields of comparative politics, business and economy, and sociology [18], as well as in general management [21], but more sporadically (and only very recently) in the field of project and general management in the energy sector. Recent publications that have applied QCA to in the energy infrastructure phenomena include the following:

- Crawford [22] used QCA to identify the organizations composing the so-called “energy policy-planning network”;
- Sander [23] investigated how oil companies developed diverse governance structures to manage similar challenges;
- Brito et al. [24] applied QCA to 39 cities that changed the fuel of urban buses to identify which combination of conditions lead to choosing compressed natural gas;
- Hennessey et al. [25] used QCA to analyse 11 projects described by four characteristics linking them to a set of co-benefits;
- Fraser and Chapman [26] used QCA to analyse 29 survey responses obtained from local officials concerning 200 of the largest mega-solar plants in Japan in an attempt to analyse the social equity impacts of the mega-solar siting process;
- Wurster and Hagemann [27] used fuzzy-set QCA to establish which conditions are linked to the growth of renewable electricity production in all 16 federal German states;

- Bakker et al. [28] have used QCA to understand how knowledge transfer between temporary inter-organizational projects and permanent parent organizations occurred, using a dataset of 12 cases;
- Verweij [29] has taken a sample of 27 Dutch road construction projects and investigated their satisfactory implementation highlighting four configurations that lead to satisfaction.

These references suggest that the research community has shown a growing interest in QCA in recent years, with increasing numbers of publications in prominent journals referring to it. Nevertheless, QCA has not been adopted to investigate energy infrastructures to the same degree as in other research disciplines [15], [18], [21].

QCA can also be adopted to leverage larger databases. Greckhamer et al. [30] have shown the potential of QCA to investigate larger data sets, both as an alternative and/or to complement other techniques, such as regression. One example is the research performed by Ning [31], who has based his study on a questionnaire-survey of 265 dwelling fit-out projects in China and focused on how the combination of formal control and trust could give rise to high project performance. Fiss [32], who has used data from a survey of 205 high-technology manufacturing firms in the UK and analysed the relationship of organisational structure characteristic with the firms' performance regarding return on assets.

Given QCA's potential to be applied to medium-sized datasets, the aim of the paper is to present how QCA can be a valuable approach to investigating energy infrastructure phenomena. This aim is achieved by applying QCA to a particular form of energy infrastructure phenomena, the decommissioning of European nuclear power plants, referred here as Nuclear Decommissioning Projects (NDPs).

1.3 Selection of the research context to exemplify QCA

Jordan et al. c summarise that QCA is appropriate when "(*1) the number of available cases is limited; (2) a comparison between an intermediate-N number of cases is desired; (3) conditions can vary both qualitatively and quantitatively; and (4) the research question probes the combinations of factors and multiple pathways that can lead to a given outcome*" (p. 1170). Moreover, QCA is particularly attractive to researchers investigating energy infrastructure phenomena for which a large dataset may be impossible to obtain. This section describes how to apply QCA, using, as an example, the phenomenon of NDP. NDPs are a good fit for QCA for the reasons summarised in Table 1.

Given that NDPs are an appropriated context for a QCA analysis, the following section provides a summary of the NDP context, before presenting the four-step process for the application of QCA.

Generic Reasons for using QCA	**Reasons why NDPs are a good fit to exemplify QCA**
It is suitable for small to medium number of cases	The number of European NDPs selected is 24
Cross-comparison of cases is possible, retaining in-depth knowledge of the cases	A cross-comparison among these NDPs is highly desired
The phenomenon to be investigated requires the use of empirical data about the project (e.g. factors that affect its outcome)	NDPs are described through their characteristics and performance, which are variables that vary both qualitatively and quantitatively
It is possible to analyse the impact of combinations of factors	The aim of this research on NDPs needs to make progress into the investigation of not only single NDP characteristics independently taken, but also their combinations, and their impact on the NDP cost overruns.
Large data sets are difficult to obtain, because constituent data are commercially sensitive or simply do not exist	It is hard to obtain a large dataset because (a) The total number of NDP in Europe is not greater than 50 and (b) given the security-sensitive nature of nuclear decommissioning it is difficult to collect information
It aims to explain causal inference	Causal inference is an important element for the decision-makers dealing with NDP

Table 1 Reasons for using QCA to analyse NDP

1.4 Relevance of the NDP research context and selection of the unit of analysis

Globally, more and more energy infrastructure is reaching its end-of-life and will enter its decommissioning phase [33], [34]. Decommissioning refers to the process of withdrawing infrastructure from service, taking it apart and deconstructing it, and when used in the context of nuclear decommissioning, also includes the need to remove the regulatory control from a facility [35].

Within the UK and the US, decommissioning projects range from small projects to multibillion-dollar megaprojects [36]–[39]. Furthermore, the costs of decommissioning energy infrastructure tend to increase, and stakeholders lack a full understating of why this happens. Additionally, most of the time, the aim of decommissioning is to restore the site to new use (i.e., reaching an "empty field" or leaving only a limited number of structures). This means that no revenue-generating assets are created at the end of the process. (This contrasts with the situation of building new infrastructure). Decommissioning also presents significant socio-economic challenges [40]–[42], as the traditional motivation to complete the project on time to benefit from the availability of the newly built infrastructure is missing.

Decommissioning projects in the energy sector can relate to offshore gas production infrastructure [43], dams [44], wave energy [45], heat pumps systems [46] and nuclear reactors [47]. Remarkably, despite their growing importance and their growing costs in several industrial sectors (e.g., nuclear and offshore oil & gas decommissioning), until now, decommissioning projects have been mostly overlooked by scholars working on the economics and management of energy infrastructure. Apart from some early remarkable research [48]–[50], the limited attention on decommissioning might be associated with the limited number of existing decommissioning projects, the limited availability of information on these projects, and the natural tendency and desire of engineers and project managers to contribute to creating new landmarks, rather than dismantling them. However, investigating the characteristics that affect decommissioning performance is urgent in order to enable such projects to be delivered effectively and not left as problems for future generations to resolve.

This paper uses the example of NDPs, primarily due to their economic relevance, and also due to the amount of official, reliable, publicly available information which exceeds other industrial sectors. In fact, concerning NDPs, publications from international organizations have recently increased in number and quality. These include reports by the International Atomic Energy Agency [51]–[53], the OECD/Nuclear Energy Agency (NEA) [54]–[56], the European Commission [57], the European Court of Auditors reports [58], [59] and others (e.g.[60]–[62]). However, these publications tend to discuss mostly the NDPs' cost estimates (e.g.[51], [56], [63]), to focus on a qualitative description and examination of a small-medium number of NDPs [58], [60], or to provide the perspective of single experts on specific topics (e.g. the authors of different chapters of [61]). However, systematic European-wide research on the NDP characteristics that affect (both individually and combined) the NDP performance (in terms of cost overruns and not discussing total original budgets) has not been presented yet. So, NDPs are the perfect examples of "middle-ground" situation to be analysed through QCA because of their sample size and the relevance of these projects. Indeed, the size of the NDP sample is a typical "middle-ground" size of 24 European NDPs, representing the ongoing European NDPs where reliable public information on the estimates at completion is available (as explained in Section 1.3).

2 Development of a four-step QCA process

Drawing from Kahwati et al. (2016), this paper elaborates four steps of crisp-set QCA. These four steps consist of:

- Step 1: the collection and selection of cases
- Step 2: the derivation and description of characteristics and performance of these cases, and their operationalization into binary variables
- Step 3: the operationalization of characteristics and performance of the selected cases
- Step 4: analysis, starting from the calculation of QCA indicators

These four steps are illustrated in Figure 1 and described in the following sections.

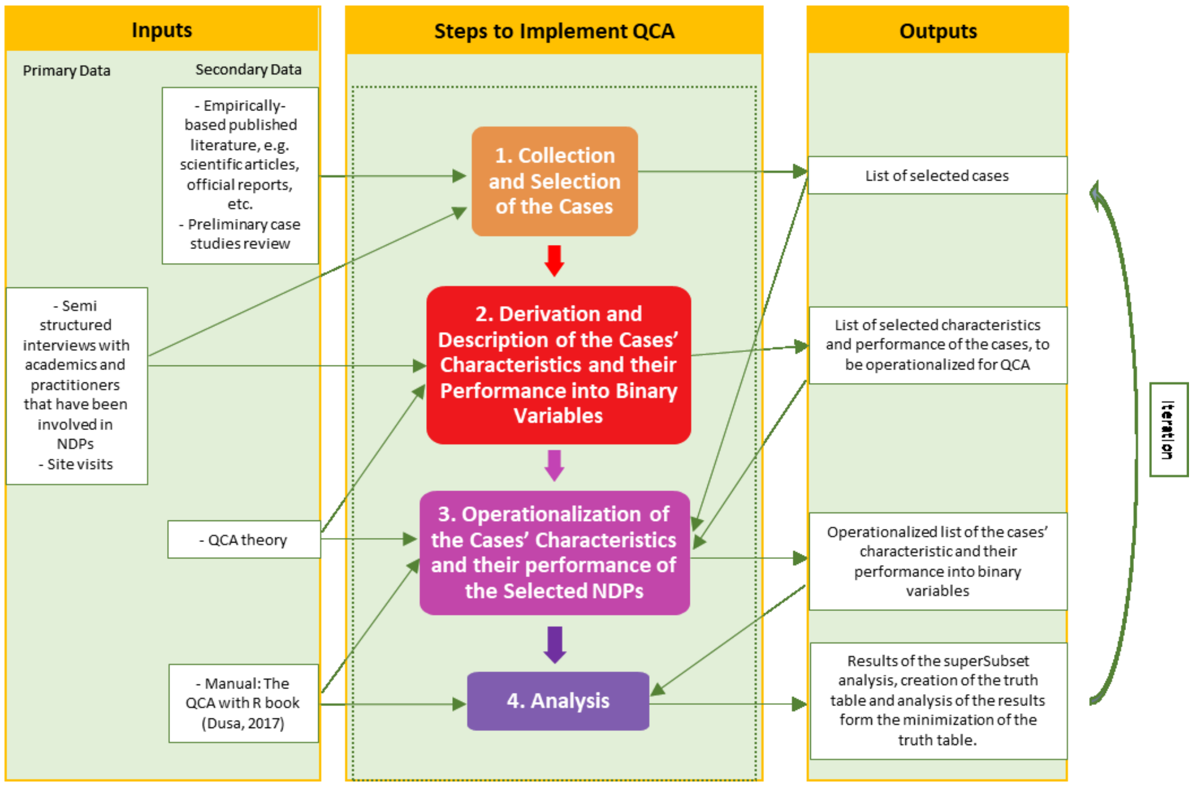

Figure 1. Steps to Implement QCA on NDPs

QCA relies on and captures causal complexity, meaning that the influence one variable has on another and the outcome(s) of interest cannot be understood fully in isolation, rather, the configuration of variables is important to understand the full effects variables have on the outcome(s) of interest [65], [66]. Equifinality, or the concept that an outcome can be achieved through different means (i.e., multiple configurations of variables or "pathways"), underpins QCA [18], [65]. Thus, our study aimed to identify all of the possible combinations of variables investigated to provide a comprehensive understanding of cost overruns in this specific context of NDPs. Asymmetry is also a causal assumption in QCA and a function of its foundation in set theory QCA [18], [65]. Unlike correlation which is fundamentally symmetrical, asymmetry in QCA reflects the concept that variables may not influence each other in the same way because variable 1 being a subset of variable 2 does not necessitate that variable 2 is a subset of variable 1. Similarly, asymmetry in QCA reflects that the configurations of variables that lead to the outcome are not necessarily the opposite of variables that lead to the negation of the outcome.

2.1 Step 1: Collection and selection of NDPs

In QCA, the number of cases has to balance the number of conditions, maintaining in-depth case knowledge. Jordan et al. [17] emphasise that, in applying QCA, "*it is beneficial to select cases that exhibit the greatest possible variety of configurations"* (p. 1163). Despite appearing as a manipulation of the dataset or a selection bias, *"this practice is appropriate for QCA because the method's logic is not probabilistic"* [17] (p.1163). QCA does not account for how many times a certain characteristic occurs, but only that it occurs.

In this study, the case selection is bounded by the number of ongoing European NDPs where information on the development of different estimates at completion is available. The NDPs selected are taken from those NDPs that are reported upon in the Power Reactor Information System (PRIS) by the International Atomic Energy Agency [67]. They were further selected on the availability of information about their costs. Sellafield NDP (in the UK) is excluded because it represents a complete outlier (as its cost estimate is greater than £160 billion, i.e. more than 70% than the overall UK ones) [68]. The Italian NDPs are excluded as the only recent publicly available information comes from local news and are deemed not to be sufficiently reliable.

2.2 Step 2: Derivation and description of NDP characteristics and performance and their operationalization into binary variables

While QCA applications have adopted numerous approaches to identify possible project characteristics, the authors adopted an inductive approach, as "*conditions are mostly selected on the basis of case knowledge and not on existing theories*" (p. 1163) [17]. Indeed, there is a lack of established theory on NDP characteristics that are important for the project performance of NDP, so these characteristics need to be gleaned from the NDP knowledge [47]. However, the deductive and inductive approaches are not mutually exclusive, "*but rather an essential continuity and inseparability between inductive and deductive approaches to theory development*" [69]. Therefore, some deductive-inductive iterations occurred.

2.2.1 Data collection and derivation of the NDP characteristics

Investigating NDP characteristics that impact on NDP performance has only recently started to attract the interest of academics and practitioners [33]. In order to review and collect NDP characteristics, the authors reviewed academic papers, reports from international organizations, and practitioner-based publications.

From this review, it emerged that the majority of academic papers on nuclear decommissioning do not focus on project management and instead discuss the technical challenges of decommissioning. However, the number and quality of reports from the international organizations and practitioner-based publications have been recently increasing. For example, Torp & Klakegg [70] examine the challenges of estimating the cost of decommissioning projects, using a Swedish NDP as a case study. These publications highlight the importance of the availability of facilities to store waste on-site, the availability and stability of funding, and the importance of overall project governance as important characteristics that affect decommissioning performance [58], [60], [61].

These publications tend to focus mostly on the NDP cost estimation process (e.g.[51], [56], [63]) or to provide the perspective of single experts on single topics, (e.g. as by authors of different chapters of [61]). A systematic study investigating the relationship between the NDP characteristics (individually and combined) and NDP cost performance is still missing.

Primary data were also gathered during semi-structured interviews, in order to make sure that the knowledge of practitioners was included in the investigation. The main open-ended question was "*In your opinion, which NDP characteristics impact most on NDP performance in terms of cost and time*?" This question was structured to enable practitioners' views to emerge without preconceptions. Time was included in the question but, given there is no publicly available information regarding the schedule of the decommissioning of European NDP, only cost was subject to the QCA application. Other questions sought to gather data on contextual independent variables including funding availability and stability, the presence of storage and/or disposal facilities on-site and/or in the country, and the regulatory-related and social challenges of NDPs [71].

Purposive sampling was used to select the interviewees [72]. Interviewees were first selected for their involvement with at least one European NDP, and at least one person with experience on each of the NDPs was interviewed. The respondents were then selected according to their seniority and their roles in the organization. Eighty-two percent of the interviewees had more than ten years in the industry; twelve percent covered various roles in different organisations within the nuclear-decommissioning industry. Experts from Sweden, Finland, Switzerland and the Netherlands were also interviewed for comprehensiveness. Interviewees included senior project and programme managers, programme enablers, head of projects, project leaders, managing directors, one head of perspective and international development, and one senior auditor of the European Court of Auditors. In total, thirty-five interviews were conducted. The interviews on average lasted forty-five minutes. The interviews were transcribed and analysed using content analysis [73], [74], broadly following the process described by [75]. Table 2 lists the NDP characteristics that have been collected during the interviews as having a potential impact on NDP performance. Other NDP characteristics were mentioned during the interviews. These include the overall governance structure, the lack of project management experience, and the need to design the infrastructure with decommissioning in mind [76].

Considering (i) the availability of reliable information collected during the literature review, (ii) the possibility to operationalize only some of the above-mentioned characteristics in a binary way, and (iii) the need to limit the number of characteristics to a maximum 6 - 7 for a number of cases between 10 and 50, six project characteristics were selected for the QCA, and their operationalization is described in Table 3. The list of characteristics was narrowed down to the characteristics in Table 3 by capturing those that could be operationalized in a binary manner and those that had reliable and adequate information available.

NDP Characteristics	Is this NDP characteristic possible to operationalize in QCA in a binary way?
Unknowns and uncertainties about the site conditions and consequent need of (additional) characterization	No, not directly. "Characterization" in the nuclear industry refers to the determination of the nature and activity of radionuclides present in a specified place [77], and it is useful to understand the site condition before the start of the NDP. However, operationalizing what "extensive characterization" is in a binary way for QCA is extremely challenging, especially at this stage of exploratory research. This area still requires further research, which could be a follow-up of the present one. However, since more extensive characterisation is needed for more complex and bigger NDPs, and more complex NDPs are the most expensive ones, the monetary size of the NDP has been operationalized for QCA.
Limited clarity of the waste routes and availability of storage and disposal facilities	Yes, this is operationalized for QCA in terms of storage facilities available on site and availability of storage facilities available in the country, as the operationalization of "clear waste routes availability" is too subjective to be operationalized in a binary way
Regulatory-related challenges	No, this would need a suite of additional assumptions to allow the operationalisation of this characteristic for QCA purposes. For example, this is described by several "sub-variables", e.g. considering the number and types of recent updates of each "key" regulations per country. Nevertheless, only limited information and knowledge on their impact on the project performance is available. Therefore, this is not operationalized in the QCA analysis presented in the paper. This characteristic can be investigated through the means of qualitative analysis (e.g. through content or thematic analysis) [78]
Availability of stable funding	Yes, this is operationalized for QCA, based on the interviewees' answers and additional references.
Government Ownership	Yes, this is operationalized for QCA in terms of governance structure
Contractual and procurement agreements	No, as "contractual and procurement agreements" would need a number of "sub-variables" to be operationalised in the context of the current research on NDPs. Indeed, there is only limited publicly available information on the most common and less common types of contractual and procurement agreements used in the selected European NDPs, and the news on this topic is mostly negative new that explain "what went wrong" (see for instance [79]), clearly providing a biased view on this topic. This characteristic can be analysed through qualitative research focusing on single case studies, analysed in-depth [80], [81].
Early and Detailed Planning	No, as "early planning" is extremely difficult to be operationalised in this research context. Information on how the NDPs were planned are not available both because most of these "original plans" go back decades and the confidentiality of this information. This characteristic can be analysed through qualitative research.
Availability of suitably qualified resources and supply chain reliability	Yes, this is operationalized for QCA, mostly based on the interviewees' answers. Contractors in the nuclear industry need to be able to demonstrate that they have robust and effective health and safety management processes, understand the significance of working in the nuclear industry, have experience in the nuclear market, have the financial strength to accept the risks and liabilities associated with large projects, have national and international standards for the management of their business, etc. [82].
Limited clarity of the final end-state	No, as "clear scope" is extremely difficult to be operationalised in this research context, as NDPs often carry big uncertainties and are affected by regulatory changes that might alter the project scope, but this information is not publicly available. This characteristic can be analysed through qualitative research.
Social-related challenges and knowledge management	No, as it is extremely difficult to operationalize in a binary way the "social-related challenges", and traditional qualitative research is more suitable for the investigation of this topic.

Table 2. NDP characteristics that have been most emphasized during the semi-structured interviews [33]

Project Characteristics	Description for the operationalization of the corresponding project characteristic	Abbreviation	Key reference in the realm of nuclear decommissioning
Project Governance	1 – the project governance is complex and multi-layered	GOVERNANCE	[58], [83] and interviews
	0 – the project governance is streamlined and not multi-layered	governance	
Funding Availability and Stability	1 – the funding is stable, and there are no changes to the funding availability	FUNDING	[54], [84] and interviews
	0 – the funding is unstable and is re-discussed yearly	funding	
Supply Chain Availability and Reliability	1 – there is an available, reliable nuclear supply chain in the country	SUPPLYCHAIN	Interviews, and recent increasing number of initiatives, e.g. [85]
	0 – there is no available, reliable nuclear supply chain in the country	supplychain	
Presence of Storage Facilities on Site	1 – storage facilities for radioactive material are available on site	STORONSITE	[86][87] and interviews
	0 – storage facilities for radioactive material are not available on site	storonsite	
Presence of Storage Facilities in the Country	1 – storage facilities for radioactive material are available in the country	STORINCOUNTRY	
	0 –storage facilities for radioactive material are not available in the country	storincountry	
Monetary Size of the NDP	1 – the monetary size of the project exceeds €1bn	ESTIMATCOMPL	[41], [88]
	0 – the monetary size of the project does not exceed €1bn	estimatcompl	

Table 3. Operationalization of the project characteristics to test against the outcome of interest

2.2.2 Derivation and description of the NDP performance

For the purpose of this exemplar application of QCA, the performance of NDPs is assessed according to their (loosely-termed) cost overruns [89]. More specifically, NDPs are clustered using different thresholds, i.e. if their cost overrun is within 10% cost overruns, as in [11], within 25%, as in [90], or within 50%, because:

- For the application of QCA the selected set of cases needed to show diversity in the outcome and can include more than one outcome [91], and
- due to the fact that, in the literature, there is limited agreement on what is the threshold above which a project should be considered affected by cost overruns.

In this case, “1” means that the NDP’s cost overrun is within a specific percentage of cost overruns, while “0” means that the NDP’s cost overrun is exceeding that percentage (in other words, it is NOT within the percentage of cost overruns specified). For example, the project “Berkeley” is NOT within 10% and 25% cost overruns (“0” in the table) but is within 50% cost overruns (“1” in the table). Conversely, a project with cost overruns higher than 50% (such as

Ignalina), is represented with “0” in all categories “Withing 10%”, “Within 25% and “Within 50%” cost overruns”.

2.3 Step 3: Operationalization of NDP characteristics and performance of the selected NDPs

The binary operationalization of both NDP characteristics and performance is based on the systematic collection of secondary data (i.e. the literature review), and primary data (i.e. semi-structured interview with experts) explained above.
Table *4* shows the raw data table of the project characteristic. “1” means that the project characteristic is present, “0” means that the project characteristic is absent. So, for example, governance was operationalized with “1” for NDPs in the UK, Bulgaria, Lithuania and Slovakia, as the governance of these NDPs is complex and multi-layered [58], [92]. Conversely, the governance of Spain, France and Germany has been operationalized with “0”, as their project governance is more streamlined and not as multi-layered.

From this table, two issues can be identified. Firstly, “Governance” and “Funding” are always characteristics in opposition, i.e., when one is present, the other is absent, and vice versa. However, this does not mean that the two are related, as the fact that the project governance is complex and multi-layered does not necessarily imply instability of funding and vice-versa. Secondly, it can be noticed that the characteristic “SUPPLYCHAIN” is present in all NDPs apart from two, and “STORINCOUNTRY” is present in all the NDPs apart from one and. This shows a limited variation of these project characteristics, which is a limitation of the current research that needs to be addressed in future research.

However, going back to case knowledge, the importance of these NDP characteristics supports (or justifies) their inclusion in the QCA. So, for example, Ignalina is the only NDP that has been operationalized as an NDP without the availability of storage in the country. This is extremely relevant, as, from the interviews, it emerged that the only Low-Level Waste storage facility in the country is a very small facility used for medical waste and that Ignalina has only very temporary storage facilities built and operational on site. This is because the waste originated in Ignalina (Lithuania), was originally supposed to be shipped back to Russia at the time of the Soviet Union, and this is now proving to be a challenge. The issues with the availability of storage facilities in Ignalina is also stressed in recent publications (e.g. [58]).

#	Selected NDPs	Project Characteristics						Project Performance: Cost Overruns		
		Project Governance	Funding Availability and Stability	Supply Chain Availability and Reliability	Presence of Storage Facilities on Site	Presence of Storage Facilities in the Country	Monetary Size of the NDP	Cost Overruns Within 10%	Cost Overruns Within 25%	Cost Overrun Within 50%
1	Berkeley (UK)	1	0	1	1	1	0	0	0	1
2	Bradwell (UK)	1	0	1	1	1	0	1	1	1
3	Chapelcross (UK)	1	0	1	0	1	0	1	1	1
4	Dounreay (UK)	1	0	1	1	1	1	1	1	1
5	Dungeness A (UK)	1	0	1	0	1	0	1	1	1
6	Harwell and Winfrith (UK)	1	0	1	1	1	1	1	1	1
7	Hinkley Point A (UK)	1	0	1	0	1	0	1	1	1
8	Hunterston A (UK)	1	0	1	1	1	0	1	1	1
9	Oldbury (UK)	1	0	1	0	1	0	0	0	0
10	Sizewell A (UK)	1	0	1	0	1	0	0	0	0
11	Trawsfynydd (UK)	1	0	1	1	1	0	1	1	1
12	Wylfa (UK)	1	0	1	0	1	0	0	0	1
13	Vandellos – 1 (Spain)	0	1	1	0	1	0	1	1	1
14	Jose Cabrera (Spain)	0	1	1	0	1	0	0	1	1
15	Chinon A (Fance)	0	1	1	0	1	0	0	1	1
16	St Laurent (France)	0	1	1	0	1	0	1	1	1
17	Bugey (France)	0	1	1	1	1	0	0	0	1
18	Brennils (France)	0	1	1	0	1	0	0	0	0
19	Chooz A (France)	0	1	1	0	1	0	0	1	1
20	Creys Malville (France)	0	1	1	0	1	1	0	1	1
21	Greifswald (Germany)	0	1	1	1	1	1	0	1	1
22	Kozloduy (Bulgaria)	1	0	0	1	1	1	1	1	1
23	Iganlina (Lithuania)	1	0	0	0	0	1	0	0	0
24	Bohunice (Slovakia)	1	0	1	1	1	1	0	1	1

Table 4. Raw Data Table

2.4 Step 4: Analysis

2.4.1 Calculation of QCA indicators

The fourth step consists of the calculation of the QCA "indicators", i.e. "consistency" and "coverage", which is performed using the QCA package in R[1], as described by Dusa (2017).

QCA identifies the necessary and sufficient configurations that lead to a certain outcome through the computation of "consistency" and "coverage". For the necessity analysis, consistency measures the level to which an outcome is a subset of a characteristic. A condition has a consistency of 100% if all the instances of the outcome (in this study, the NDP performance in terms of cost overruns) comprise a subset of the instances of the condition (in this study, the NDP characteristic). Low consistency means that the configuration is not supported by empirical evidence and may be considered "less important" than other configurations with higher consistency. Coverage refers to the number of cases where the configuration is valid. Coverage is used as a measure to calculate how much of the entire outcome is explained by the condition and indicates the percentage outcome that can be explained using given pathways. High coverage shows that a given pathway represents many cases [13]. However, "*this does not mean that pathways with low coverage are unimportant, as QCA is not probabilistic. Despite this, knowing which pathways to a given result are seen more frequently can help guide practitioners to interventions that may be more likely to apply to many cases*" [94] (p.8).

Additionally, to calculate the sufficiency of a configuration, the indicator called "Relevance of Necessity" (RoN) is computed, which allows checking whether the necessary condition is

[1] The QCA package in R has been preferred to other software, like "Tosmana" and "fsQCA" (Thiem and Dusa 2013) because of how these software deal with prime implicants. Prime implicants are the final surviving, minimal expressions of the logical minimisation (Dusa 2017) which is the core of QCA (as explained in the next sections). According to Baumgartner and Thiem (2017), at the time of writing, "Tosmana" and "fsQCA" are less transparent in presenting the complete QCA solution than the code in R. Therefore, R is selected as the software of preference.

trivial or not. The creation of the truth table allows the analysis of sufficiency, "*which reduces the causal complexity by outlining the logical combinations of all conditions and linking these combinations to the presence or the absence of an outcome*" (Cebotari & Vink 2013, p.307). The truth table can then be logically minimized. Logical minimisation is the process by which the empirical information is expressed in a more parsimonious yet logically equivalent manner, by looking for commonalities and differences among cases that share the same outcome. Chatterley et al. (2013, p.413) explain that "*QCA uses Boolean minimization logic to reduce conditions to the most logically succinct combinations of conditions that produce the outcome of interest*". So, in simple terms, the truth table minimisation consists of comparing the truth table rows that present the same outcome but differ for one condition and reducing the number of conditions accordingly. Lastly, the superSubset analysis "*explores every possible necessity relation, for individual conditions, or conjunctions (even though conjunctions are redundant), as well as all possible disjunctions of conditions that are necessary for a given outcome*" [93]. In this study, the superSubset analysis was performed three times for the three outcomes of interest: within 10% cost overruns, within 25% cost overruns, and within 50% cost overruns. The interpretation and discussion of the QCA results for these three outcomes are presented in the next sections.

2.4.2 Results from the calculations of QCA indicators

The superSubset analysis performed on the outcome of interest "within 10% cost overruns" neither highlights single characteristics nor a combination of characteristics that present both consistency and coverage higher than the cut-off point of 0.75, which is the "*lowest permitted*" cut-off point to consider results relevant [29]. Moreover, the truth table shows only one configuration that presents perfect consistency, which refers to case number 22 of Table ***4***.

More interesting are the results of the analysis of the outcome of interest "within 25%" and "within 50%" cost overruns. At first glance, the results from the superSubset analysis seem to show that the availability of a reliable nuclear supply chain (SUPPLYCHAIN) and the presence of storage facilities available in the country (STORINCOUNTRY) are necessary conditions for cost overruns lower than 25% (and therefore also 50%). However, it is possible to detect that this is a too hasty interpretation of the results, in two ways: (i) going back to the raw data of Table ***4***, where a more accurate look highlights the limited diversity of the binary characteristics SUPPLYCHAIN and STORINCONUTRY, and (ii) checking their Relevance of Necessity[2]. Indeed, Dusa [93] envisages putting a threshold of 0.6 for the RoN. Therefore, the consideration of RoN threshold of 0.6 in the analysis of "cost overruns within 25%" leaves two solutions, i.e.: "governance + STORONSITE" and "FUNDING + STORONSITE". This suggests that a combination of a streamlined governance structure and the presence of a storage facility for radioactive material on-site, as well as the combination of having stable funding for the NDP and storage facilities available on-site, are both related to cost overruns lower than 25%.

[2] The RoN defines the explanatory power of a condition and was introduced to distinguish between necessary and trivial conditions: the smaller the RoN, the more trivial the condition (Laux 2015, p.87)(Schneider & Wagemann 2012, p.236)

In the analysis of "cost overruns within 50%", RoN of 0.6 leaves the same two solutions highlighted above (i.e. "governance + STORONSITE" and "FUNDING + STORONSITE"), plus the following solutions:

- "governance+ estimatcompl"
- "FUNDING + estimatcompl"
- "GOVERNANCE + STORONSITE + ESTIMATCOMPL"
- "funding + STORONSITE + ESTIMATCOMPL".

The latter two solutions suggest that (i) a complex governance, associated with the availability of storage facilities on-site, for the case of larger projects and that (ii) funding discussed on a yearly basis, together with the availability of storage facilities on-site, in the case of larger projects are related to cost overruns lower than 50%. However, these two solutions should be cautiously considered since they both present a "borderline" consistency of 0.75.

Even more thought-provoking is the solution "FUNDING + estimatcompl", which suggests that stable funding for the cases of smaller projects is related to cost overruns lower than 50%.

Results of both the outcome of interest "within 25%" and "within 50%" cost overruns are condensed in Figure 2, where significant results are highlighted respectively in light blue and light orange. Here, "incN" stands for "inclusion of necessity" (normally called "consistency" in the analysis of a combination of characteristics in QCA), and "CovN" is the "coverage of necessity".

Results are also presented in the Appendix in tabular form.

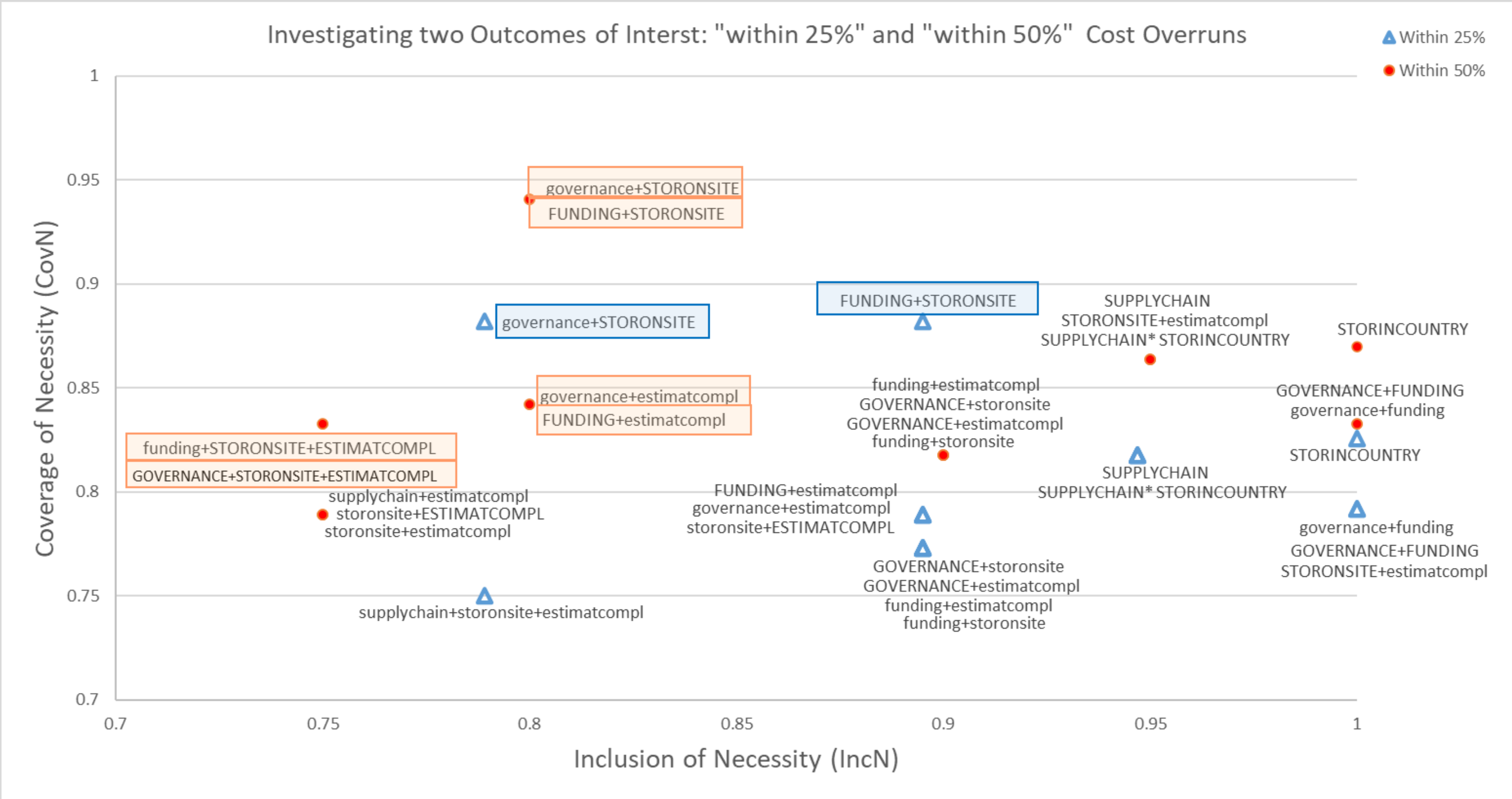

Figure 2. superSubset of the NDP characteristics both for the outcome "within 25%" and "within 50%" cost overruns. "IncN" stands for inclusion of necessity", "CovN" stands for "coverage of necessity". Noteworthy results are highlighted in light blue and light orange. The meanings of lower and uppercase are explained in Table 3.

3 Discussion

This paper provides both a methodological and a practical contribution, by:

- Presenting QCA as a valuable approach for undertaking research on energy infrastructure phenomena,
- Providing an example of a step-by-step approach to implement QCA, illustrated by the QCA application on NDPs.

QCA is a valuable approach to research energy infrastructure phenomena because it is suitable where the number of cases available is in the range of 10-50, which is often the case in the energy sector. Indeed, several methods address single case study or a very small number of case studies (i.e. following Yin [10] or Eisenhardt [8]). Similarly, there are numerous publications based on the analysis of larger data sets (such as the work by Flyvbjerg [96] and Merrow [90]). However, research with a small to medium sample size is more limited. Here, QCA can yield significant insight by facilitating systematic cross-case comparisons that retain case complexity and allow for generalizability, and by using data that are both qualitative and/or quantitative, as graphically depicted in Figure 3.

For example, QCA could be used to analyse the project performance of infrastructure whose sample size lays in a small-medium range, such as nuclear reactor under construction [97] or the ones that are about to restart [98]. Moreover, it could be used in completely different energy-related fields, such as investigating storage plants in operations [99] or assessing the overall energy efficiency performance of different countries [100].

The main shortcoming of QCA compared to a case study approach is that the variables that can be considered are limited in number. So, researchers and practitioners have to be aware of these limitations and must use their contextural knowledge in understanding the implications of the results. However, the authors argue that, as part of the "toolbox" of different possible ways to investigate energy phenomena, QCA should play a more important role. In other words, the step-by-step approach for QCA presented in this paper does not aim to substitute any of other qualitative or quantitative data analysis approaches. On the contrary, it describes an additional approach that researchers and practitioners should be aware of and could use. If more than one approach can be used, i.e., where approaches overlap in Figure 3, then the researchers who reached the same results using different approaches could increase the robustness of their conclusions. Conversely, if QCA contradicted previously-achieved results, this would trigger important follow-up questions that will need to be investigated more in-depth relying upon case knowledge and theory. So, in both situations, QCA could provide valuable insight into the relationships between variables and outcomes.

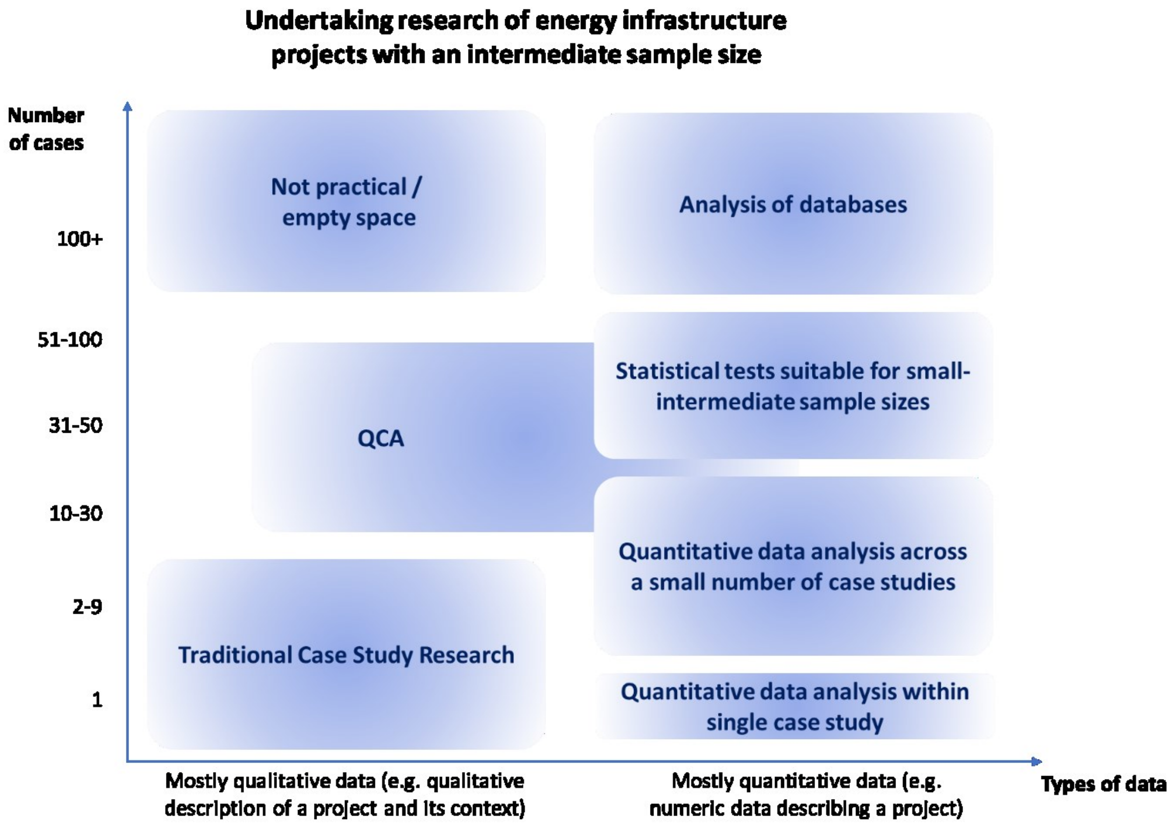

Figure 3. Undertaking research with different types of data and different number of cases available

Specifically referring to the application of QCA on NDPs, the authors argue that, to interpret the results of the application of QCA, it is important to refer to contextural knowledge of the selected NDPs [13]. Drawing from this knowledge, preliminary insights on the results provided by the application of QCA on NDPs include the fact that the presence of storage facilities on-site is present in the minimised solutions, which reinforces the common knowledge about the fact that a clear waste management plan is needed to guarantee NDPs with better performance. The two cases where the presence of storage in the country does not appear in the results are (i) when the project is smaller and funding is stable, (ii) when the project is smaller and the project governance is not complex and not multi-layered. This suggests when the project size is smaller, the fact of having stable funding or a simpler governance structure is linked to cost overruns being within 50%.

These results are limited by the case diversity. Only limited logical minimisation is achievable without inserting additional assumptions. This limitation should be addressed in future research.

4 Limitations and future research

This research is intended to pave the way to a wider application of QCA to energy infrastructure phenomena, particularly for researching emerging topics such as decommissioning. This research has identified two key issues that are simultaneously limitations and opportunities for future research.

The first limitation is methodological and concerns the use of crisp-set QCA. Future research can explore fuzzy-set QCA and multi-value QCA [23], [30]. These techniques work for non-binary variable and potentially could provide more nuanced or comprehensive results [65], [101]–[103]. In this follow-up research, it may be possible to compare fuzzy QCA and other approaches with the initial results of this crisp-set QCA presented in this paper. It would be interesting to explore if the extra complexity introduced by using more advanced techniques is compensated by the results achieved.

The second limitation is related to the dataset and relates to both the cases analysed and the characteristics incorporated into the QCA. The analysis is limited by the diversity of the NDPs, which reduces the sophistication of analysis. For example, two of the characteristics selected to be tested against the project performance have a limited variability across cases, and the time dimension has been not accounted for (but could be considered for future research, e.g. using temporal QCA [104], [105]). This research could be further extended by using probabilistic criteria, adjustment factors, and frequency thresholds [106], as well as by applying the "theory-enhanced standard analysis. This would enable investigation of the logical reminders that contradict common sense, formal logic, or both [107], Additionally, the analysis of 24 NDPs allows for some generalisation, but it restricts the extent to which the single NDP can be known in-depth. This is the trade-off between single case-studies and cross-case analysis and is hindered by the techno-socio-economic complexity of the nuclear industry. So, this research is a foundation for a better understanding of the characteristics that affect project performance.

Future research should also include the investigation of project performance in term of socio-economic and environmental aspects. It could also expand the sample outside Europe to incorporate NDP in the USA, Russia and Japan.

QCA can yield significant insight that qualitative case study research does not provide as it offers an efficient way to quantify the impact of combined characteristics on the outcome of interest. However, QCA has the limitation that the number of variables that can be analysed is limited. While QCA retains some case complexity in its analysis, case study analysis is useful to explore that complexity more holistically. When data availability is limited across cases (e.g., such as limited publicly available data as often occurs with NDPs), researchers may need to rely on case study analysis to explore the influence of a particular phenomenon that may not be possible to systematically compare through QCA.

5 Conclusions

The empirical analysis of energy projects is very frequent in energy journals, but the “middle-ground” of 10 to 50 cases is not often researched. Despite this limited number of studies, this “middle-ground” is populated by an interesting sample of projects, such as the construction of long pipelines or the construction and decommissioning of dams and nuclear power plants or even the analysis of energy policies across different countries. The contribution of this research is to present QCA as a valuable approach to do this type of research in the energy sector. This is demonstrated through the application of this method to analyse NDPs.

Due to the limited existing research and limited quality of data and information available about NDPs, this application has limitations on its extendibility. Nevertheless, with this investigation, the authors wish to underline the importance of progressing research investigating the effect of combining different characteristics. For example, the preliminary findings presented in this paper suggest that some NDP characteristics combined, such as stable funding and availability of storage on-site, have an impact on the NDP cost overruns. These results stimulate further discussions on how NDP characteristics (both taken individually and combined) influence NDP performance.

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Disclosure statement

No potential conflict of interest is reported by the authors.

Appendix

Table 5 and Table 6 respectively present the results related to the outcome of interest within 25% cost overruns and withing 50% cost overruns. The coloured lines are the results also highlighted in Figure 2.

Outcome of Interest: within 25% cost overruns			
superSubset() analysis	**RoN**	**inclN**	**CovN**
governance+STORONSITE	0.778	0.789	0.882
FUNDING+STORONSITE	0.778	0.895	0.882
governance+estimatcompl	0.556	0.895	0.789
FUNDING+estimatcompl	0.556	0.895	0.789
storonsite+ESTIMATCOMPL	0.556	0.895	0.789
supplychain+storonsite+estimatcompl	0.444	0.789	0.75
SUPPLYCHAIN	0.333	0.947	0.818
SUPPLYCHAIN* STORINCOUNTRY	0.333	0.947	0.818
STORONSITE+estimatcompl	0.333	0.947	0.818
GOVERNANCE+storonsite	0.286	0.895	0.773
GOVERNANCE+estimatcompl	0.286	0.895	0.773
funding+storonsite	0.286	0.895	0.773
funding+estimatcompl	0.286	0.895	0.773
STORINCOUNTRY	0.2	1	0.826
governance+funding	0	1	0.792
GOVERNANCE+FUNDING	0	1	0.792

Table 5. Results related to the outcome of interest "within 25%" cost overruns

Outcome of Interest: within 50% cost overruns			
superSubset() analysis	**RoN**	**inclN**	**CovN**
governance+STORONSITE	0.875	0.8	0.941
FUNDING+STORONSITE	0.875	0.8	0.941
GOVERNANCE+STORONSITE+ESTIMATCOMPL	0.667	0.75	0.833
governance+estimatcompl	0.625	0.8	0.842
FUNDING+estimatcompl	0.625	0.8	0.842
supplychain+estimatcompl	0.556	0.75	0.789
storonsite+estimatcompl	0.556	0.75	0.789
storonsite+ESTIMATCOMPL	0.556	0.75	0.789
SUPPLYCHAIN	0.4	0.95	0.864
SUPPLYCHAIN* STORINCOUNTRY	0.4	0.95	0.864
STORONSITE+estimatcompl	0.4	0.95	0.864
GOVERNANCE+storonsite	0.333	0.9	0.818
GOVERNANCE+estimatcompl	0.333	0.9	0.818
funding+storonsite	0.333	0.9	0.818
funding+estimatcompl	0.333	0.9	0.818
STORINCOUNTRY	0.25	1	0.87
governance+funding	0	1	0.833
GOVERNANCE+FUNDING	0	1	0.833

Table 6. Results related to the outcome of interest "within 50%" cost overruns

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