




A structured approach to prioritise industrial energy efficiency measures by assessing feasibility criteria

E du Toit

 **orcid.org/0000-0002-6677-2236**

Dissertation submitted in fulfilment of the requirements for the degree *Master of Engineering in Mechanical Engineering* at the North-West University

Supervisor: Dr J Pascoe

Examination: November 2021

Student number: 25956124

ACKNOWLEDGEMENTS

This dissertation would not have been possible without the support of several people. I would like to express my gratitude to the following individuals:

- I am grateful for the financing and support of this dissertation provided by Mine Clever (Pty) Ltd.
- Thanks to Dr Janine Pascoe for your guidance and support throughout each stage of this dissertation. Your assistance is greatly appreciated.
- Thanks to Dr Waldt Hamer for your direction and mentorship throughout this study.
- Thank you to my parents and my brother – your love and support have carried me throughout my studies. Words fail to express my gratitude.
- Thank you to my friends and colleagues for your support.
- I would like to thank God for granting me the knowledge and capability to complete this study.

ABSTRACT

Title: A structured approach to prioritise industrial energy efficiency measures by assessing feasibility criteria

Author: E du Toit

Supervisor: Dr J Pascoe

Keywords: *energy efficiency measures, incentives, feasibility, prioritisation, multi-criteria decision-making*

The increasing importance of energy management is evident in the growing global energy demand as well as in the incentivisation of energy efficiency by the South African government. Despite the large potential in industry, there are multiple barriers that prevent implementation of energy efficiency measures (EEMs). Contributing factors include the implementation cost of proposed EEMs, the associated project uncertainty, and the multitude of EEMs to choose from. These factors can be mitigated by using energy efficiency incentive programmes, conducting feasibility studies, and prioritising the implementation of initiatives using verified techniques, respectively.

There is, however, a lack of a structured approach to obtain a prioritised list of feasible EEMs. A need therefore exists for an approach to determine what EEMs are feasible to implement and how incentive programmes can improve the business case of these measures. Additionally, there is a need for a prioritisation technique of feasible EEMs.

The research objective of this study is to develop an approach that meets the following requirements: considers financial incentive programmes; systematically determines the feasibility of EEMs; and prioritises the implementation order of the feasible EEMs using multi-criteria decision-making.

Various energy efficiency incentive programmes are researched to gain an understanding of the potential benefits of utilising incentives. An extensive literature review of both technical and financial feasibility criteria for EEMs is conducted. Technical criteria include factors that influence the performance and complexity of EEMs such as energy savings, ease of implementation, and maturity of the technology. Financial criteria include profitability indicators and cost implications.

A detailed review of various prioritisation criteria for EEMs is conducted. Subsequently, different prioritisation techniques are reviewed, and a suitable multi-criteria prioritisation technique is chosen to design the structured approach. The structured approach consists of two phases. Phase 1 of the

structured approach entails sorting the relevant reviewed feasibility criteria into three structured stages of feasibility. Phase 2 of the structured approach comprises the weighting and verification of relevant prioritisation criteria via questionnaires completed by energy management experts.

The developed structured approach is validated by applying it to a large and complex industrial facility with 161 proposed EEMs as part of the facility's energy management programme. The feasibility of these initiatives was systematically determined by applying Phase 1 of the structured approach. Furthermore, the structured approach yielded a prioritised list of 18 feasible EEMs.

The recommended implementation of the feasible EEMs has potential energy efficiency savings of 1.3 TWh per annum, estimated cost savings of R332 million, and estimated incentive shareholder value of R338 million. The case study results prove that the research objective was met and highlight the need for a structured approach to determine the feasibility of EEMs in order to prioritise them.

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LIST OF ABBREVIATIONS

Abbreviation	Description
AHP	Analytical Hierarchy Process
AIJ	aggregation of individual judgments
ALCC	annualised lifecycle cost
CDM	Clean Development Mechanism
CHP	combined heat and power
CI	consistency index
CR	consistency ratio
CS	cost savings
DSR	Design Science Research
EE	energy efficiency
EEM	energy efficiency measure
ELECTRE	elimination et choix traduisant la réalité
ES	energy savings
ESCO	energy services company
GHG	greenhouse gas
GS	Gold Standard
HVAC	heating, ventilation, and air conditioning
IEA	International Energy Agency
IFC	International Finance Corporation
IPP	Industrial Policy Project
IRR	internal rate of return
MCDM	multi-criteria decision-making

Abbreviation	Description
MCEP	Manufacturing Competitiveness Enhancement Programme
MOV	method of verification
M&V	measurement and verification
NPV	net present value
O&M	operation and maintenance
PI	profitability index
PP	payback period
PROMETHEE	Preference Ranking Organisation Method for Enrichment Evaluation
RI	random index
ROR	rate of return
SANAS	South African National Accreditation System
SEforALL	Sustainable Energy for All
TOPSIS	Technique for Order of Preference by Similarity to the Ideal Solution
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VCS	Verified Carbon Standard
WPM	Weighted Product Method
WSM	Weighted Sum Method

NOMENCLATURE

AFD Green Energy Fund	A finance programme for renewable energy and small-scale energy efficiency projects related to the manufacturing of green products in South Africa ⁱ .
carbon credits	A tradable permit that provides the holder of the credit the right to emit a certain amount of carbon dioxide or an equivalent of another greenhouse gas [1].
carbon tax	A taxation instrument imposed on CO ₂ -equivalent emissions above predetermined thresholds [2].
Clean Development Mechanism (CDM)	A mechanism created to allow countries to reach their emission reduction targets. The mechanism allows developed countries to invest in emission reduction projects in developing countries for which an emission reduction credit is received [2].
CO ₂ -equivalent	A standard unit of measure for greenhouse gases (GHGs) where each GHG has a global warming potential relative to CO ₂ that enables the conversion to equivalent CO ₂ emissions [2].
Design Science Research (DSR)	A research methodology that entails the invention of a new artefact that addresses a general type of problem and subsequently evaluates the usefulness of the artefact for solving the problem [3].
energy efficiency (EE)	The ratio between the amount of useful output obtained and the associated energy input [4-6].
energy efficiency gap	The phenomenon where energy efficiency technologies are not utilised to the degree that would seemingly be justified from an environmental and economical perspective [7-9].

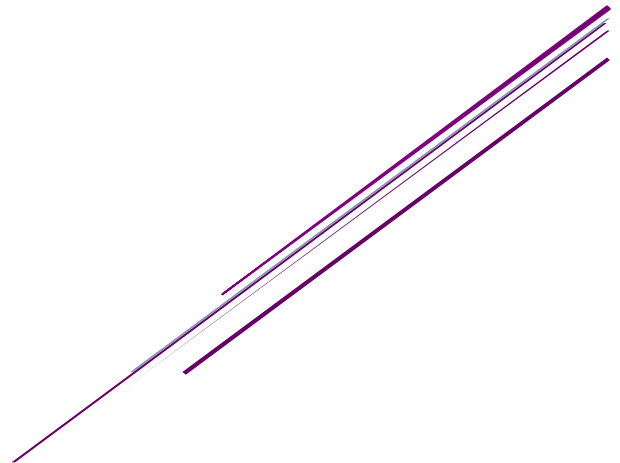
ⁱ IDC. "AFD Green Energy Fund." IDC. <https://www.idc.co.za/afd-green-energy-fund> (accessed Nov. 3, 2021).

energy efficiency incentive	An offering to encourage a reduction in the total amount of energy spent to maintain a given level of output [10].
energy intensity	The amount of energy used in delivering a certain level of output or activity [11].
Gold Standard (GS)	A voluntary carbon credit trading regime [2].
greenhouse gas (GHG)	Gases that are included in carbon footprint assessments, namely carbon dioxide (CO ₂), methane (CH ₄), nitrous oxide (N ₂ O), sulphur hexafluoride (SF ₆), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs) [2].
Manufacturing Competitiveness Enhancement Programme (MCEP)	A financial grant programme supporting manufacturing enterprises with interventions that improve their competitiveness [12].
Section 12B	An accelerated tax depreciation allowance for certain assets used in the production of renewable energy [13].
Section 12I	A tax deduction of the costs of new and unused manufacturing assets for projects that use improved EE and cleaner production technology [13].
Section 12L	A tax allowance for measured and verified energy efficiency savings against an approved baseline [11].
Verified Carbon Standard (VCS)	A voluntary carbon credit trading regime [2].

CHAPTER 1:

INTRODUCTION AND

LITERATURE



1 INTRODUCTION AND LITERATURE

1.1 Preamble

The opening chapter serves as background to the study. Section 1.2.1 highlights the importance of energy efficiency (EE) by the discussion of issues related to the growing global energy demand. The potential for industrial EE is illustrated in Section 1.2.2. This is done by considering the extent of energy usage in industry, ambitious industrial EE targets, and a discussion of the multiple industrial energy efficiency measures (EEMs) that can be implemented.

Despite the technical potential in industry, various barriers to EE exist. The most prevalent barriers to industrial EE are identified in Section 1.2.3 through an analysis of known barriers provided by literature. A critical literature review is conducted in Section 1.3 to determine whether the most prevalent barriers to industrial EE are adequately addressed. From the analysis of the literature, the problem statement and research objectives for the study are formulated in Section 1.4.

The research methodology is discussed in Section 1.5 and a conclusion is provided in Section 1.6. An overview of the dissertation is given in Section 1.7. Appendix A provides supplementary information to the chapter.

1.2 Energy efficiency landscape

1.2.1 Importance of energy efficiency

Global energy demand is rapidly increasing with a forecasted growth of between 30% and 50% by 2050 [7, 14]. The rapid growth in energy demand is set to outstrip energy supply [15, 16] which may have several fiscal, environmental, and social implications [17].

The projected energy demand is cause for concern regarding global energy security. Fears over energy security have led to unprecedented resource exploitation [17] that may ultimately lead to resource depletion [5]. The depletion of energy resources will force countries to rely on imported energy, leading to rising energy costs [17].

If global energy demand surpasses supply, global greenhouse gas (GHG) emission reduction targets might not be reached [5]. At the current trend, average global temperatures are expected to rise by at least 1.5°C above pre-industrial levels between 2030 and 2052 [18]. This increase ultimately fuels

the adverse effects of climate change such as the loss of ecosystems, water shortages, and food insecurity [18]. Failure to reach emission reduction targets may also increase the vulnerability of impoverished communities, resulting in a variety of socio-economic issues [18]. Additionally, the reduction in GHG emissions has been found to enhance firm value if investors regard emission reduction as valuable [18].

Sustainable economic development is highly reliant on meeting the required energy demand [17, 19, 20]. The adequate availability of energy contributes to stable energy prices and improved productivity that enhance industrial competitiveness [17]. Enhanced industrial competitiveness and stable energy prices alleviate poverty through job creation and lower domestic energy costs, respectively [17].

Improving EE is widely considered to be an effective strategy for addressing the concerns related to energy demand and GHG emission control [21]. EE refers to the efficient utilisation of an energy carrier or resource [22]. It is the inverse of energy intensity, which is the amount of energy used in delivering a certain level of output or activity [11]. EE is broadly defined as the ratio between the amount of useful output obtained and the associated energy input [4-6].

Improvements in EE that result in reduced energy demand can improve energy security by increasing fuel availability, accessibility, and affordability [6, 8, 15, 21, 23]. Energy security alleviates the pressure on local energy resource exploitation. The need for imported energy is thus reduced, resulting in lower energy prices [21].

EE is a cost-effective means of reducing energy consumption and thereby mitigating GHG emissions [6, 8, 15, 21, 23]. EE notably reduces direct emissions from fossil fuel combustion and consumption as well as indirect emissions from electricity generation [21]. Reduction of GHG emissions may also have financial benefits since an increasing number of governments are imposing a financial cost for carbon dioxide emissions associated with energy generation [21].

EE also has a variety of macro-economic impacts such as increased productivity and reduced cost of production [17, 21]. Increased productivity enables enhanced competitiveness and the creation of sustainable employment opportunities [17]. New industries, such as energy services companies (ESCOs), may grow due to the reduction of energy waste, thereby creating job opportunities [17]. The reduction in energy demand due to EE results in more affordable domestic energy prices, thus alleviating poverty [21].

Although applicable to all sectors of the economy, energy-efficient operations have gained widespread use in the industrial sector. The technical potential for industrial EE is illustrated in Section 1.2.2.

1.2.2 Technical potential for industrial energy efficiency

Industry refers to the economic activity related to the processing of raw materials and the manufacturing of products. Technical potential refers to the EE potential that is available considering the technologies available but with no consideration of the economics [5]. The technical potential for industrial EE is illustrated in two ways in this section. First, the extent of industrial energy consumption and ambitious EE targets are discussed. Thereafter, a discussion of the multitude of EEMs that are available is provided.

Industrial energy consumption and energy efficiency targets

The South African energy demand profile is shown in Figure 1-1 [24]. Figure 1-1 shows that industrial energy consumption accounts for more than 50% of the South African energy demand.

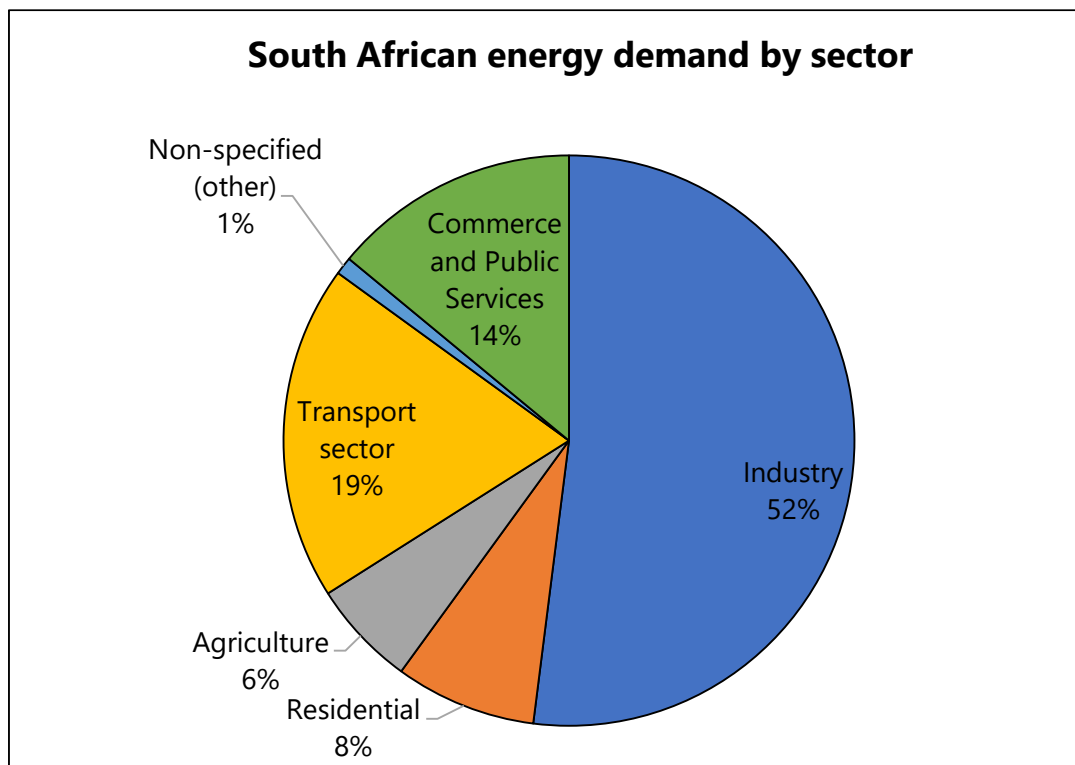


Figure 1-1: South African energy demand by sector (adapted from [24]).

Furthermore, according to Fawkes *et al.* [5], the International Energy Agency (IEA) [21], and Reinaud *et al.* [23], industrial energy consumption accounts for approximately a third of the global energy

demand. Since industry is a major energy consumer, any decrease in industrial energy consumption will significantly contribute to the achievement of national as well as global energy reduction targets. This highlights the importance of energy-efficient industrial operations.

Table 1-1 shows a summary of the estimated technical potential for EE for various sectors of industry if best practice commercial technologies are implemented [5].

Table 1-1: Technical savings potential for industrial sectors (adapated from [5]).

Industrial sector	Low – high estimates of technical savings potential (GWh/annum)
Chemicals/ petrochemicals	1.4 – 1.8
Iron and steel	0.64 – 1.3
Cement	0.70 – 0.84
Pulp and paper	0.36 – 0.42
Aluminium	0.08 – 0.12
Other non-metallic minerals & non-ferrous	0.14 – 0.28

The technical potential for industrial EE is further illustrated by the magnitude of global EE estimations (a maximum of 4.76 GWh per annum) and targets. The IEA has projected that the global industry has the potential to produce nearly twice as much value per unit of energy in 2040, compared to current levels [25].

The IEA estimates that energy usage can be reduced by 18% in the cement sector, 26% in the pulp and paper sector, and 11% in the aluminium sector if current best EE technologies are utilised [26].

The European Union has committed to a 32.5% EE target by 2030 relative to the projected energy usage in 2030 [27, 28]. Similarly, Turkey’s National Energy Efficiency strategy targets a 20% reduction in energy intensity by 2023, compared to 2011 levels [17].

The Sustainable Energy for All (SEforALL) initiative, launched in September 2011 by the United Nations (UN), has set an objective to double the global rate of improvement in EE by 2030 [21]. EE is also utilised as a tool within the context of the United Nations Framework Convention on Climate Change (UNFCCC) to assist member countries in meeting climate change mitigation goals [17].

Furthermore, the South African government has proposed ambitious reduction targets for the industrial and mining sector. A 16% reduction target in the weighted mean specific energy

consumption in manufacturing by 2030, relative to a 2015 baseline, has been proposed [4]. Furthermore, a 40 PJ cumulative annual saving target from EEMs in the mining sector has been set [4]. Specific EE targets for various countries as well as the estimated improvement possible highlight the technical potential for EE in industry.

Multitude of possible energy efficiency measures

The diverse nature of industry emphasises the technical potential for EE: industry consists of multiple subsectors with various processes and numerous EEMs that can be implemented [21]. Initiatives range from replacing individual pieces of equipment to complete facility retrofits [21].

There are a variety of system processes that are universal to the industrial sector. These system processes include heating, ventilation, and air conditioning (HVAC) systems; lighting; process heating; compressed air networks; motors such as fans and pumps; steam generation and distribution systems; and process cooling systems [5, 29].

Each system process in turn has various universal EEMs that can be implemented thereon. General universal categories of industrial EEMs are as follows [5, 29]:

- maintenance activities
- retrofitting of existing equipment and systems
- replacement of existing equipment with more efficient technologies
- matching supply and demand:
 - switching off equipment when no longer required
 - correct sizing of equipment to match the demand
 - installation of variable speed drives on motorised equipment
- use of process control
- minimising losses:
 - fixing of leaks
 - minimising the number of heat transformations on working fluids such as steam
 - insulation of equipment and working fluid distribution systems
 - water and condensate recovery
- heat recovery and/or combined heat and power (CHP) applications

Consequently, the summary above shows that numerous universal EEMs exist for implementation on general industrial system processes. This is because industry consists of multiple subsectors with thousands of industrial processes and numerous ways in which EEMs can be designed and implemented [21]. For example, maintenance activities leading to EE can be applied to different industrial system processes, such as steam systems, motors, and HVAC systems. Similarly, heat recovery and/or CHP applications can be applied to process cooling systems, steam systems, and process heating systems.

The variety of EEMs that can be implemented on common industrial systems is graphically summarised in Figure 1-2 with a green circle indicating the possibility of implementing a specific EE category on an industrial system process. Figure 1-2 emphasises that various universal EEMs can be implemented on a broad range of industrial processes. The wide variety of EEMs that can be considered for implementation on common industrial process systems showcase the technical potential for EE.

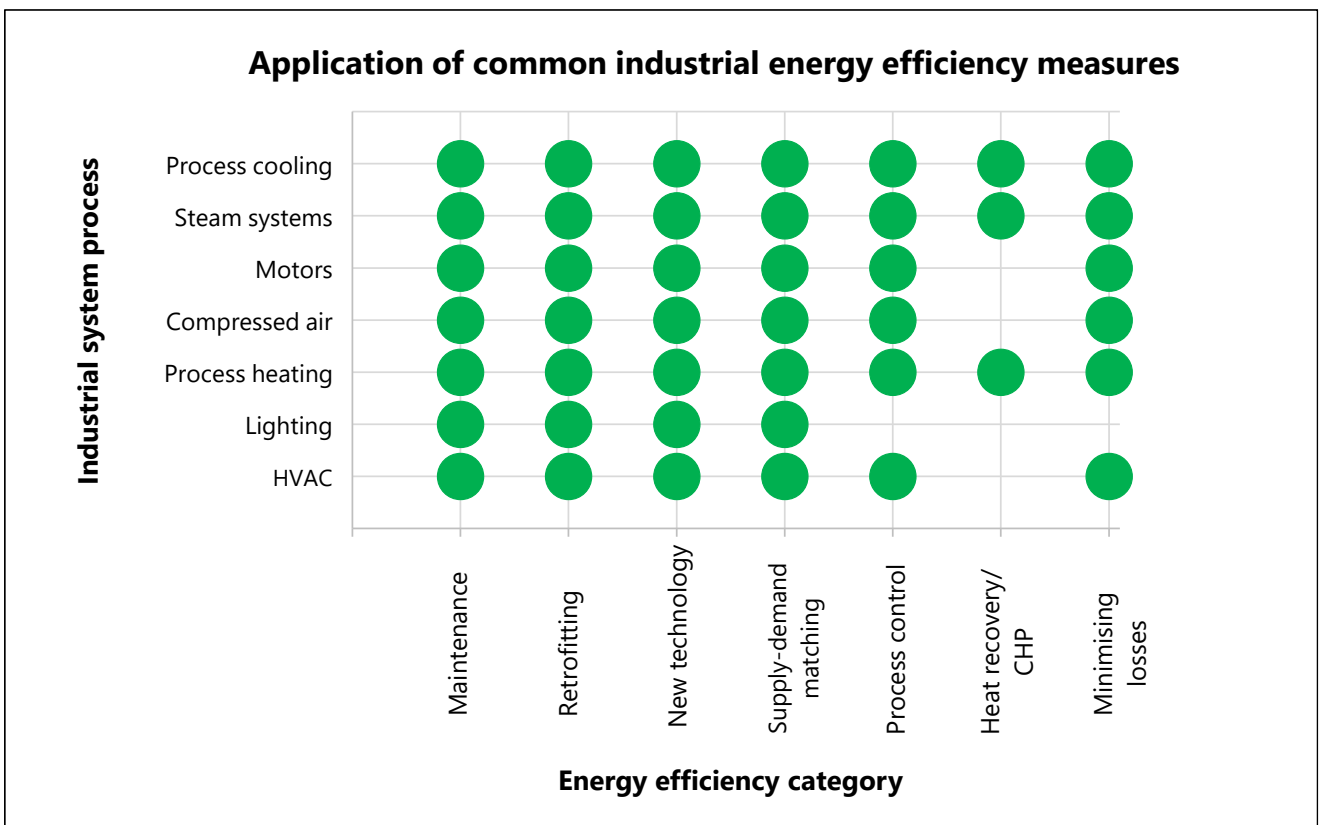


Figure 1-2: Application of EEMs to various industrial system processes.

In addition to the multiple universal EEMs available across different industries, various industry-specific and site-specific EEMs can also be implemented. The technical potential for industrial EE is

thus illustrated by the combination of the multiple universal EEMs and industry-specific initiatives that can be implemented on a wide variety of industrial system processes.

Despite the technical potential illustrated thus far, industrial EE is not utilised to its full potential due to a variety of challenges. A review of common challenges in industrial EE is presented Section 1.2.3.

1.2.3 Challenges in industrial energy efficiency

Despite the technical potential for EE, there exists an “energy efficiency gap” where EE technologies are not utilised to the degree that would seemingly be justified from an environmental and economical perspective [7-9]. The EE gap can be attributed to a variety of barriers to EE. *Barriers to EE* is a term used in literature and refers to a field of study where the obstacles that impede the implementation of feasible EE projects are researched [6].

Several studies have been conducted to identify, quantify, and categorise barriers to EE. The taxonomy of Sorrell *et al.* [30] is widely accepted and implemented in the categorisation of EE barriers [31]. Figure 1-3 provides a summary of the classification of the barriers to EE [30].

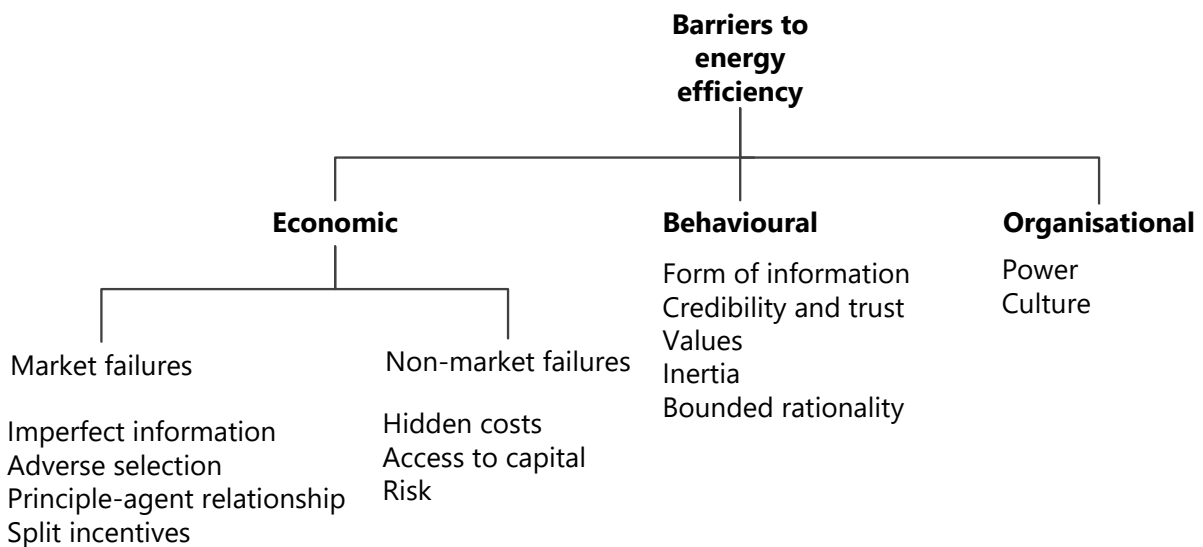


Figure 1-3: The Sorrell *et al.* classification of barriers to EE [30].

Figure 1-3 shows that Sorrell *et al.* [30] classified barriers to EE into three distinct perspectives, namely Economic, Behavioural, and Organisational. Each perspective in turn is comprised of various barrier categories. A description of each barrier category is provided in the following paragraphs.

Imperfect information is a category of barriers that describes the lack of information on available EEMs. This may include a lack of awareness on available measures, the unavailability of information

regarding EEMs, and inaccurate information [32, 33]. *Imperfect information* may also refer to the scarcity of information regarding the technical performance of EE technologies as well as the cost of researching and identifying EEMs [34, 35].

Adverse selection refers to barriers where the producers of energy-efficient technologies are better informed on the characteristics and performance of the technologies than the buyers [30].

The **principle-agent relationship** barrier category describes a situation where there is a lack of trust between members at different levels in an organisation [30]. The lack of trust may lead to the demand for unreasonable project performance, resulting in the neglect of cost-effective EEMs [30].

The **Split incentives** category refers to the appropriation of the benefits of EEMs to parties that were not involved in the implementation thereof [32, 35].

Hidden costs is a category of barriers that relate to unforeseen or undetermined expenses that were not included in the investment model [36]. *Hidden costs* include unforeseen costs related to production disruption, the adaption of production scale, and maintenance costs [32]. This category also includes unforeseen costs relating to the gathering and analysing of potential EEMs [35].

Access to capital is a barrier category relating to the lack of affordability of EEMs and the financing thereof [32]. The high capital cost of EEMs as well as the lack of access to capital are frequently cited as widespread barriers to EE [7, 8, 31, 37-39]. Many companies may not have access to internal or external capital to fund high initial cost projects [33]. Access to internal funds may be limited due to a lack of liquidity and therefore lucrative high-cost projects cannot be financed internally [35]. Furthermore, internal funds may be inhibited due to internal budget procedures and constraints [35]. The availability of external capital may be restricted and the cost of borrowing capital may not be cost-effective [40].

The **Risk** category refers to uncertainty regarding the success of EEMs from both a technical and financial viewpoint. A widespread barrier to EE is the uncertainty regarding the technical feasibility and technical risks of industrial EEMs [8, 31, 37-39]. Technical risks include the appropriateness of the energy-efficient technology for the specific site and application, the uncertainty of whether the initiative will work, and possible production disruptions. Financial risks include the uncertainty and volatility in future energy prices that may inhibit investments in EEMs due to more stringent investment criteria [40].

Heterogeneity refers to the variability of the costs and performance of an EEM, based on the specific situation of the company where the measure is to be implemented [32]. Therefore, a technology that may be cost-effective on average may not be economically viable in individual cases [40].

Form of information refers to the lack of attention that an EEM measure may draw due to the form in which the information is presented to the decision maker [32].

The **Credibility and trust** category refers to the perceived credibility of the information on EEMs and the suppliers thereof [36]. Consequently, there may be a lack of trust in the information provided [36].

The **Values** category relates to concern for the environment and moral obligation to EE [36]. A lack of values related to EE may prevent the implementation of EEMs [32].

Organisational and individual behaviour is largely driven by established habits and routines. The difficulty in evoking behaviour change is described by the **Inertia** barrier category [36].

The **Bounded rationality** category is descriptive of two modes: (1) conflicts of interest within an organisation, and (2) decision making that relies on rule of thumb due to constraints on time, attention, resources, and the ability to process information [36, 40].

The **Power** category refers to the unequal distribution of influence within a company that may lead to the neglect of EEMs [32]. The lack of influence of energy managers can lead to the low priority of EEMs [31].

Culture refers to the fundamental values of an organisation that may inhibit the implementation of EEMs [36].

Cagno *et al.* [40] has highlighted the need for an extended taxonomy for barriers to EE due to missing elements from the taxonomy of Sorrell *et al.* [30]. A notable additional barrier category addition from Cagno *et al.* [40] is the **Other priorities** category which refers to both the Economic and Organisational perspectives in the taxonomy of Sorrell *et al.* [30].

From an Economic perspective, **Other priorities** may refer to alternative investments that enjoy a higher urgency than investment in EE [41]. The necessity to choose between EEMs and other investments highlights that companies have limited financial resources. Therefore, *Other priorities for capital investments* can be viewed as an indicator of a lack of *Access to capital*. Additionally, *Other*

priorities may also refer to organisational limitations of time and human resources available for EE [40].

It is important to note that various implicit interactions can be identified between the barrier categories described thus far [40]. Since the gathering and analysing of EEMs may result in unexpected costs, limited time and human resources can be associated with the *Hidden costs* category. However, limited time and human resources are also encompassed in the *Bounded rationality* barrier category.

Furthermore, limited human resources with the technical skills required to implement EEMs can be attributed to both the *Bounded rationality* and *Risk* categories. Additionally, there is an interactive effect between the *Risk* and *Hidden costs* categories since technical risks such as production disruptions may result in unforeseen expenses.

The adaptation and extension of barrier taxonomies are commonly applied in the analysis and categorisation of EE barriers [31, 40, 41]. Therefore, based on the need to account for elements not explicitly addressed in the Sorrell *et al.* taxonomy, as well as interactive effects between the different barrier categories, an adapted classification of the barriers to EE is proposed.

It is suggested that the category *Other priorities for capital investments* be included under the *Access to capital* category. Furthermore, to highlight its widespread inhibitive effect on the implementation of EEMs, it is proposed that a **Lack of time and human resources** be established as a separate category. Since a lack of time and human resources refer to organisational shortcomings, the category was added to the *Organisational* group. Based on the proposals discussed, the Sorrell *et al.* taxonomy depicted in Figure 1-3 has been adapted accordingly, as shown in Figure 1-4.

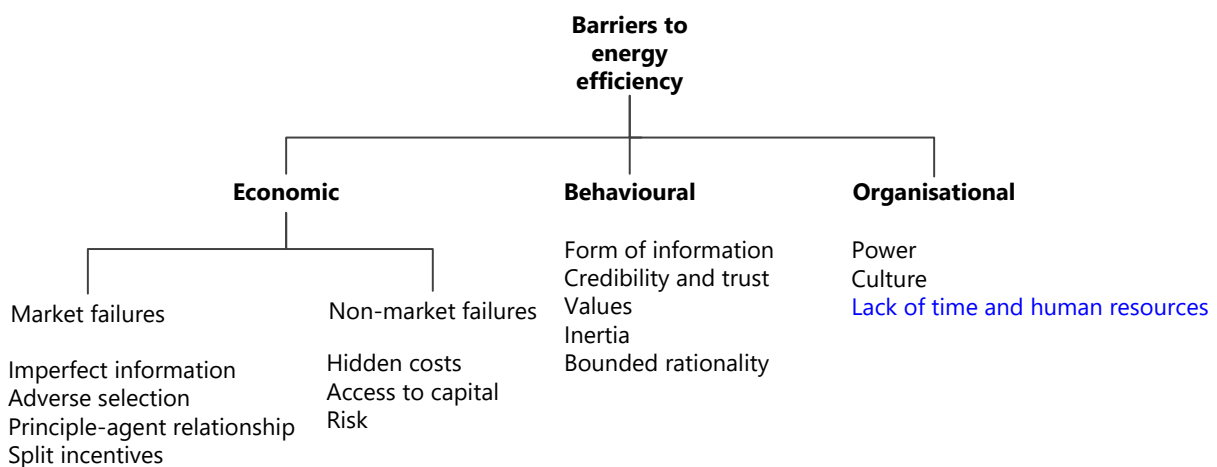


Figure 1-4: An adaptation of the Sorrell *et al.* taxonomy (adapted from [30]).

Various studies that evaluate barriers to industrial EE were reviewed to identify and categorise the most prevalent barriers to EE. Table A-1 in Appendix A provides a summary of the studies that were considered with the main barriers emphasised by each study [31, 33-36, 41-57]. Each barrier was subsequently categorised according to the classification presented in Figure 1-4. The occurrences of the various barriers to EE from Table A-1 were quantified and are presented in Figure 1-5.

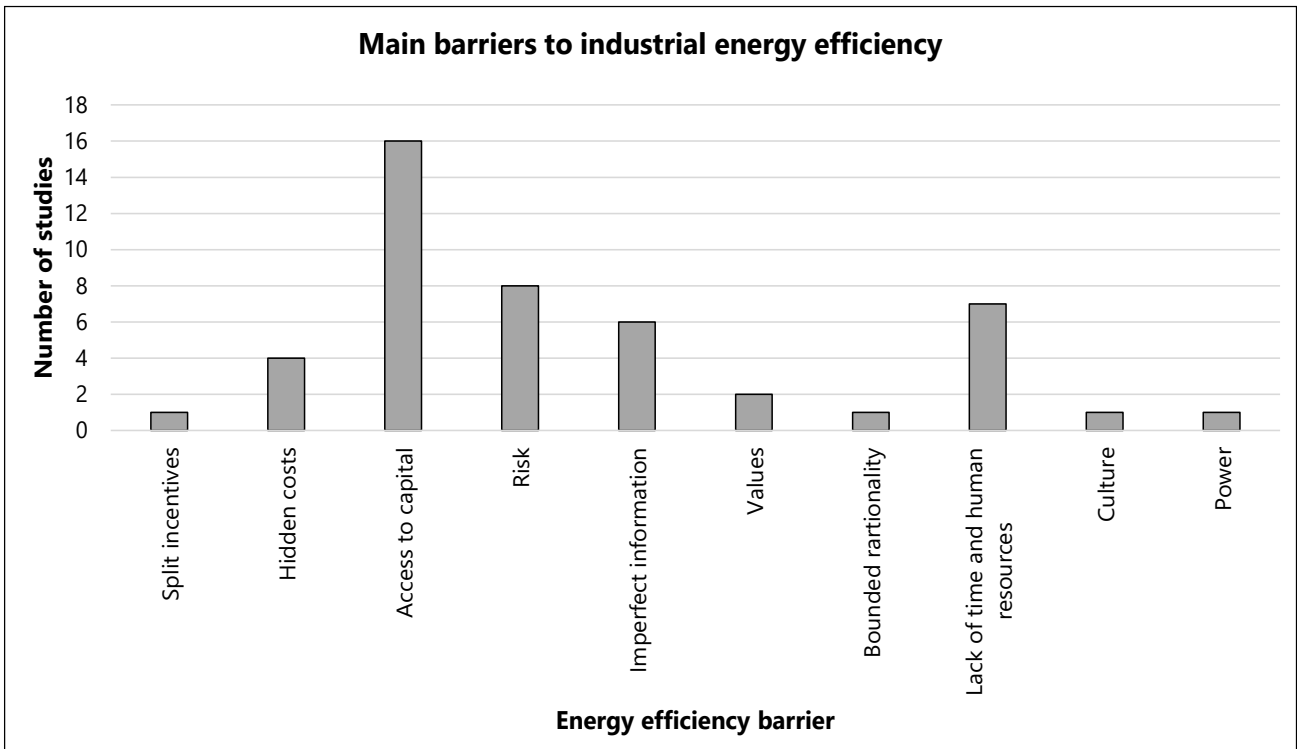


Figure 1-5: The number of occurrences of each EE barrier category [31, 33-36, 41-57].

The three most prevalent barrier categories identified in Figure 1-5 in descending order are *Access to capital*, *Risk*, and a *Lack of time and human resources*. A comprehensive review of 22 studies was performed and therefore the findings are considered representative of the challenges faced in industry. These barrier categories emphasise that a shortage of financial resources, project uncertainty, and limited time and human resources are central themes to explain the EE gap.

Since the various barrier categories have interactive effects, the mitigation of the most common barrier themes may inadvertently address the less common barriers as well. For example, constraints on time, attention, and resources in the *Bounded Rationality* barrier category may be alleviated by addressing the limited time and human resource barrier theme.

Similarly, by mitigating the project uncertainty associated with implementing EEMs, *Hidden costs* may be reduced since technical risks such as production disruptions are less likely to occur.

Mitigation strategies are needed to overcome these barrier themes in order to realise the technical potential for industrial EEMs that was illustrated in Section 1.2.2. Existing mitigation measures to the three barrier themes are reviewed in the following section.

1.3 Evaluation of multiple energy efficiency measures

A literature review was conducted to determine the way in which the most prevalent barriers to industrial EE are mitigated. Mitigation strategies for the three barrier themes identified in Section 1.2.2, namely a shortage of financial resources, project uncertainty, and limited time and human resources, were researched. Three mitigation measures were identified from the literature review, namely the use of financial incentives, conducting feasibility studies, and the prioritisation of EEMs. Each mitigation measure is elaborated on in the following paragraphs.

To address the shortage of financial resources available to EEMs, many governments have incentivised industrial EE [6, 12, 58, 59]. An EE incentive is defined as an offering to persuade customers to decrease the total amount of energy used for a given level of output, without compromising the output quality [10]. Financial incentives include rebates, subsidies, grants, and other financing tools for EEMs [10].

Tax incentives and low-interest loans for EEMs are considered as one of the most suitable ways to increase EEM investment viability [60]. Prindle [10] found that direct financial incentives such as rebates, discounts, and subsidies have a high impact on overcoming capital investment barriers. Upfront investment for EEMs through grants and subsidies may help to alleviate the upfront capital cost of funding.

Various South African financial incentives, such as the Section 12L tax rebate, aim to alleviate the initial capital investment required for implementation of EEMs [11]. Tax rebates received for historically implemented EEMs may be used to settle outstanding loans for implemented EEMs, thereby lowering the cost of borrowing capital. Alternatively, tax rebates received for historically implemented EEMs may be used to fund future EEMs, thereby alleviating the high initial capital cost of some EEMs. These benefits may motivate companies to revise its internal capital budgeting procedures to prioritise the funding of EEMs.

The above discussion therefore substantiates that financial incentives are intended to address the shortage of financial resources barrier by overcoming high capital costs and a lack of access to funding.

A project feasibility analysis is proposed to address the prominent barrier of project uncertainty. A feasibility analysis is a common project management technique employed to determine the viability of EEMs [61]. A project feasibility investigation is a tool to mitigate project uncertainty [61]. This is done by examining the ability of the project to deliver value that surpasses the efforts and resources required to implement the project [62]. A review of the proposed project's feasibility is used to mitigate both the financial and technical risks associated with EEMs [61].

Due to the magnitude of potential EEMs in industry, companies face the time-consuming process of evaluating, selecting, and prioritising the implementation order of viable EEMs from a large pool of potential initiatives [63]. Since companies have limited time and human resources, a consistent approach for the feasibility assessment is needed and the implementation order of viable EEMs should be prioritised.

Studies that evaluate multiple EEMs concurrently were consulted to determine to what extent the three mitigation measures identified are applied. The following questions are used to evaluate the studies:

1. Do the studies consider the use of incentives to address the shortage of financial resources barrier theme?
2. Do the studies evaluate the financial feasibility of the projects to address the project uncertainty barrier theme?
3. Do the studies evaluate the technical feasibility of the projects to address the project uncertainty barrier theme?
4. Do the studies prioritise the EEMs to address the limited time and human resources barrier theme?
5. If the studies prioritise EEMs, what criteria are used?

An evaluation of the studies based on the questions posed above is presented in Table 1-2. A colour key is used to distinguish between affirmative and negative answers to the questions posed above: green shading represents affirmative answers while orange shading represents negative answers. If the answer to question 4 is affirmative, question 5 was answered by listing the criteria used to prioritise the initiatives in the "Criteria used for prioritisation" column of Table 1-2.

Table 1-2: State of the art on prioritising EEMs by addressing prominent barriers to EE.

Study	Incentive programs	Financial feasibility	Technical feasibility	Prioritisation	Criteria used for prioritisation
[63]					Discounted return on investment
[64]					
[65]					Complexity of the EEM Effect of the EEM
[66]					Financial criteria Technical criteria
[67]					
[68]					
[69]					Cost
[70]					
[71]					
[72]					Cost of conserved energy
[73]					Cost
[74]					
[75]					Cost of conserved energy
[76]					
[77]					Total investment cost
[78]					Financial criteria Technical criteria Social criteria Environmental criteria
[79]					
[80]					

From Table 1-2, it is evident that there is great variation in the detail, quality, and scope of the concurrent analysis of multiple EEMs. Although all the studies completed some form of financial feasibility analysis to address financial uncertainty, only one study utilised incentives to improve the business case of the EEMs. Therefore, even though the financial component of the project uncertainty barrier theme is widely addressed, the shortage of financial resources is not adequately addressed.

Since only a third of the studies considered the technical feasibility of initiatives, it is evident that there is not a strong emphasis on the technical verification of EEMs. The lack of technical verification in literature illustrates that it is difficult to determine what parameters should be considered to determine whether a project can be practically implemented. The technical components related to the project uncertainty barrier theme are therefore not adequately addressed by the literature that was studied.

Only half of the studies ranked the implementation order of the EEMs and thus the limited time and human resources barrier theme was not extensively addressed. Furthermore, since various technical and financial parameters should be considered and weighed against one another to determine the order of project implementation, it was expected that the studies would use multiple criteria when prioritising EEMs. Yet only three of the studies recommend the order of prioritisation based on more than one criterion.

Although all the studies in Table 1-2 utilised at least one of the three mitigation strategies identified, none of the studies addressed all three barrier themes concurrently. It is therefore evident that current literature approaches to mitigate the most prevalent barriers to EE are lacking.

1.4 Problem statement and research objective

The discussion in Section 1.3 highlighted that the three most prevalent barrier themes to EE are not adequately addressed in literature. Incentive programmes are under-utilised despite the improvement of the business cases for EEMs that they facilitate. The analysis in Section 1.3 further highlighted that there is no clear and structured approach to determine what EEMs are technically and financially feasible to implement. Furthermore, the current approach to project prioritisation is lacking since multiple criteria are not utilised to rank the order of implementation of viable EEMs.

There is a need for a structured approach that systematically addresses all three prevalent barrier themes by utilising the mitigation measures identified from literature. The structured approach needs to utilise incentives to address the shortage of financial resources that companies may face. The financial and technical feasibility of EEMs should be evaluated by the structured approach to address project uncertainty. Furthermore, to address the limited time and human resources of companies, the approach should use multiple criteria to prioritise the projects that are deemed feasible.

Formulated from the problem statement above, the research objective of this study is to develop a structured approach to prioritise industrial EEMs that meet the following requirements:

1. The approach considers available financial incentives as part of the analysis of EEMs.
2. The approach systematically determines the technical and financial feasibility of EEMs.
3. The approach uses multiple criteria to prioritise the order in which the feasible projects should be implemented.

1.5 Research methodology

Chapter 1 highlights the need for a structured approach to address the three main EE barriers identified. The Design Science Research (DSR) methodology is used to design the structured approach. DSR entails the invention of a new artefact that addresses a general type of problem and subsequently evaluates the usefulness of the artefact for solving the problem [3].

DSR was chosen as the research methodology since this study involves the invention of an artefact (the structured approach) to solve a real-world problem (overcoming the three prevalent EE barriers).

DSR consists of three cycles, namely relevance, rigour, and design. The relevance cycle initiates the DSR by providing the problem to be solved and the requirements for the research. The relevance cycle links the research environment with the design process. The rigour cycle links the application of the existing knowledge base from literature to the design process. The design cycle entails the construction and evaluation of the artefact [81].

The document structure is based on the three DSR cycles as shown in Figure 1-6. Chapter 1 provides context on the environment and links to Chapter 2 via the relevance cycle. Chapter 2 represents the rigour cycle by utilising existing knowledge from literature to design the structured approach. Chapter 2 further encompasses the design cycle through the development of the structured approach.

Chapter 3 is also included in the design cycle since the structured approach is evaluated by application to a case study. Furthermore, Chapter 3 forms part of the relevance cycle by evaluating whether the requirements of the research are met.

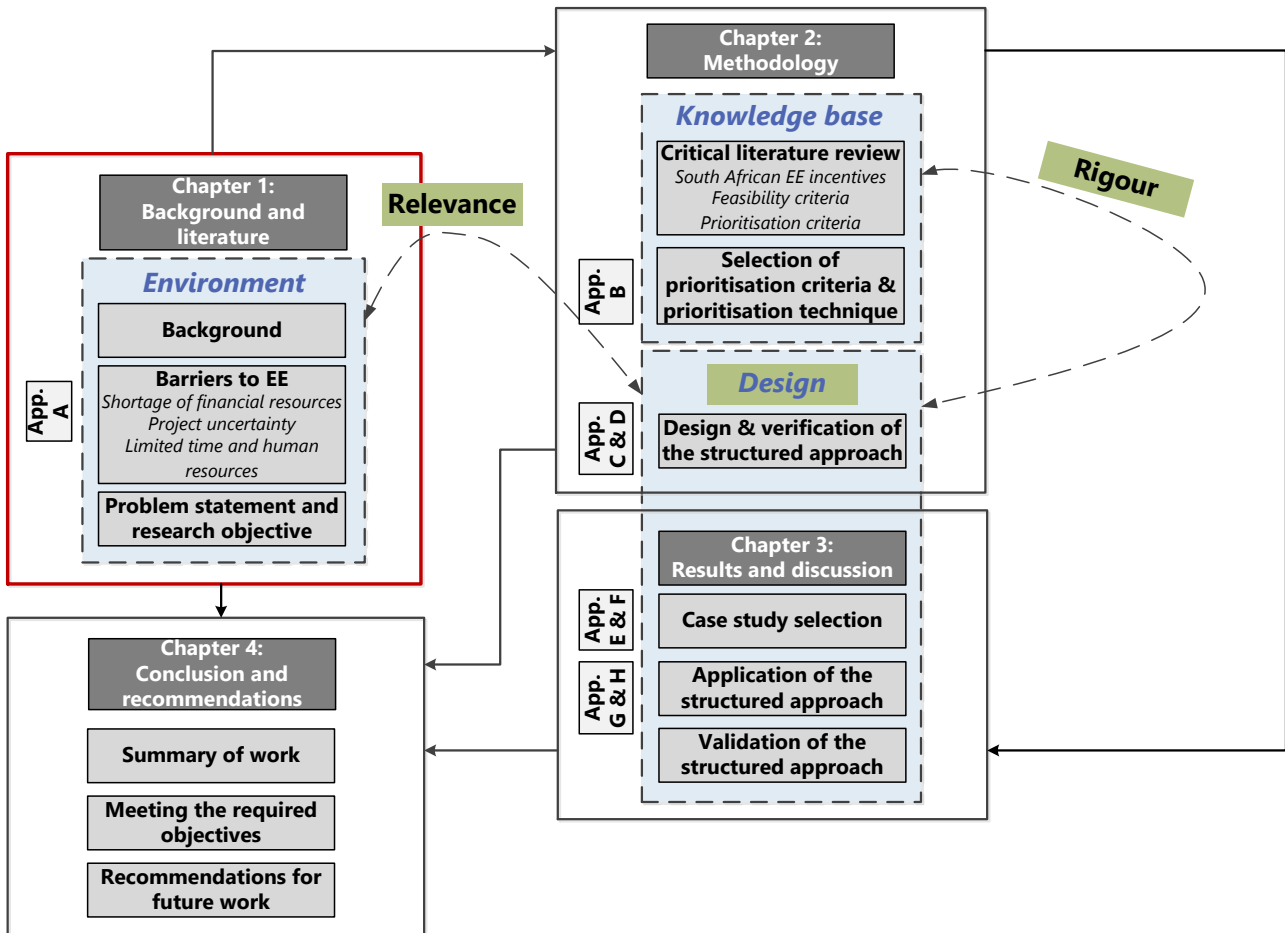


Figure 1-6: Research methodology and document structure.

1.6 Conclusion

Chapter 1 provides background to the study. Section 1.2.1 discussed the importance of EE, and the technical potential for industrial EE is illustrated in Section 1.2.2. Section 1.2.3 highlights that various barriers to EE exist. Notable barrier themes identified from the literature are a shortage of financial resources, project uncertainty, and limited time and human resources.

A critical literature review is conducted in Section 1.3 to determine how the most prevalent barriers to EE are addressed during the evaluation of multiple EEMs. Section 1.4 highlights the need for a clear and structured approach to determine the feasibility of multiple EEMs before prioritisation via multi-criteria decision-making (MCDM). Additionally, the need to include EE incentives in the structured approach is identified. Section 1.5 discusses the research methodology used to design the structured approach.

1.7 Overview of the dissertation

Chapter 1

The focus of Chapter 1 is to provide background to the study. A critical review of the importance of EE, industrial EE technical potential, and key challenges to achieving EE are provided. The problem statement and research objective stem from the background provided. The research methodology is discussed, and an overview of the dissertation is provided. Supplementary information on the barriers to EE identified from literature are provided in Appendix A.

Chapter 2

Chapter 2 starts with a review of the South African EE landscape. Thereafter, a review of literature is conducted to identify feasibility criteria critical to the success of EEMs. The prioritisation criteria for EEMs and the chosen prioritisation technique are subsequently discussed. Chapter 2 further contains the development of the structured approach. Chapter 2 concludes with a discussion on the verification of the approach. Supplementary information to Chapter 2 is provided in Appendix B to Appendix D.

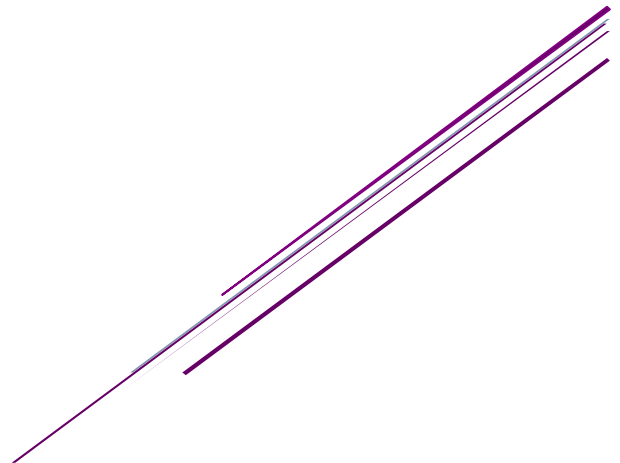
Chapter 3

The developed structured approach is validated in Chapter 3 by applying it to a case study. A large industrial facility with 161 potential EEMs is used as the case study. The structured approach yields a list of 18 feasible EEMs that are prioritised. Three methods are used to validate the structured approach. Appendix E to Appendix H provide supplementary information to the chapter.

Chapter 4

Chapter 4 provides a summary of the dissertation and discusses how the study objective was met. Recommendations for future work and a conclusion to the dissertation are also provided.

CHAPTER 2: METHODOLOGY



2 METHODOLOGY

2.1 Preamble

Chapter 1 illustrated the need for a structured approach to prioritise multiple energy efficiency measures (EEMs). A review of the South African energy efficiency (EE) incentive landscape, various feasibility criteria, prioritisation criteria, and prioritisation techniques are required before the structured approach can be developed.

Figure 2-1 shows that Chapter 2 involves the three cycles of the Design Science Research (DSR) methodology. Chapter 2 consists of a critical review of relevant literature (Section 2.2 to Section 2.5) that links the existing knowledge base to the design of the structured approach through the rigour cycle of the DSR methodology.

Chapter 2 further contains the design and verification of the structured approach which are representative of both the design and relevance cycles of the DSR research methodology.

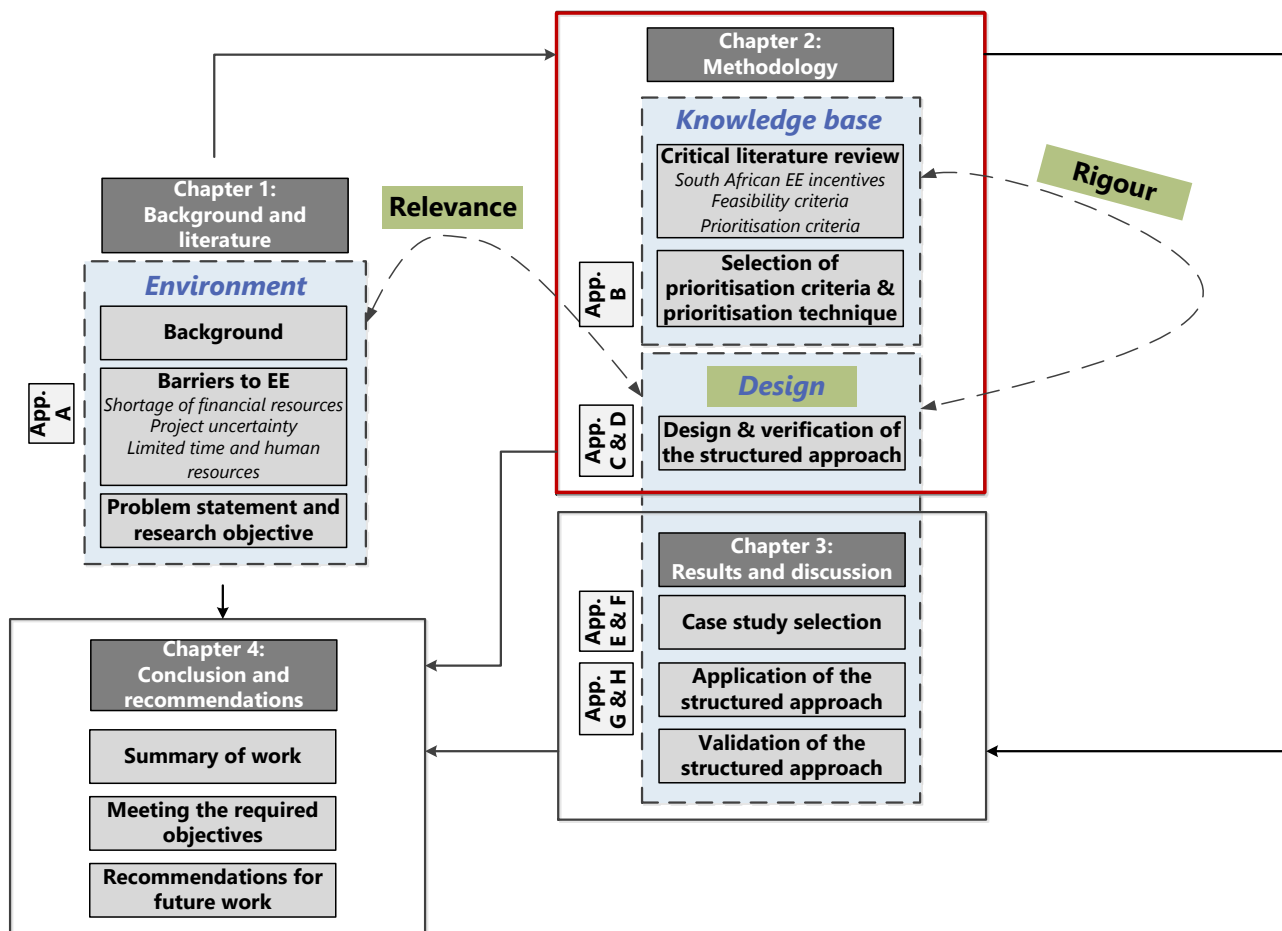


Figure 2-1: The structure of Chapter 2 within the research methodology.

The critical literature review is divided into sections according to the requirements of the research objective provided in Section 1.4. The first requirement of the structured approach is to utilise incentives as part of the analysis of EEMs. Therefore, a review of the available South African EE incentives is provided in Section 2.2.

The second requirement of the structured approach is to determine the financial and technical viability of EEMs. Section 2.3 thus contains an analysis of feasibility criteria that are deemed critical to the successful implementation of an EEM.

The third requirement of the approach is the use of multiple criteria to prioritise EEMs. Prioritisation criteria are reviewed and compiled in Section 2.4. Section 2.5 provides a discussion of available multi-criteria prioritisation techniques from which a relevant prioritisation technique is chosen.

The literature reviews conducted in Section 2.2 to Section 2.5 are consequently used to design the structured approach in Section 2.6. The structured approach consists of two phases, namely the feasibility assessment (Phase 1) and the prioritisation of the feasible EEMs (Phase 2). The designed approach is verified in Section 2.7.

This chapter only includes the information important for development of the structured approach with supplementary detail provided in Appendix B to Appendix D.

2.2 Review of South African energy efficiency incentives

To achieve the proposed energy reduction targets, the South African government has incentivised industrial EE. A variety of financial incentives are available in the South African energy landscape and have been evaluated by various authors [12, 13, 29, 82]. Notable successful energy-related tax incentives include Sections 12B, 12I, and 12L of the Income Tax Act [12, 13, 29, 82]. Additionally, carbon credits and other EE incentives, such as the Manufacturing Competitiveness Enhancement Programmeⁱ(MCEP), the AFD Green Energy Fundⁱⁱ and finance assistance through loans are available.

Section 12B of the Income Tax Act is an accelerated depreciation allowance for certain assets used in the production of renewable energy [13]. A 50%-30%-20% depreciation is allowed over a three-year period for most of the methods of renewable electricity generation. In the case of electricity

ⁱ MCEP. "About MCEP." MCEP.co.za. <http://mcep.co.za/about/> (accessed Nov. 3, 2021).

ⁱⁱ IDC. "AFD Green Energy Fund." IDC.co.za. <https://www.idc.co.za/afd-green-energy-fund> (accessed Nov. 3, 2021).

generation from photovoltaic solar energy of less than 1 MW, the taxpayer may deduct 100% of the value of the solar power system as a depreciation expense in the year that the plant is brought into use [83].

Section 12I of the Income Tax Act is an Industrial Policy Project (IPP) that allows a tax deduction of between 35% and 100% of the costs of new and unused manufacturing assets for projects that use improved EE and cleaner production technology [13]. The tax incentive aims to develop the South African manufacturing sector by investing in manufacturing assets and the training of personnel [12].

Section 12L of the Income Tax Act offers a tax incentive for measured and verified EE savings against an approved baseline. The initial incentive value of 45 cents per kilowatt hour equivalent of EE savings was increased to 95 cents per kwh in 2015 to further incentivise EE [11]. Independent SANAS-accredited Measurement and Verification (M&V) bodies are required to measure and verify the value of the energy savings [13]. However, renewable energy projects do not qualify for the allowance and the allowance is not granted if a concurrent EE savings benefit is received from a government agency [13].

With the Carbon Tax Act effective since June 2019, the South African government has instated several mechanisms to reduce the carbon tax liability of taxpayers. One such mechanism is the provision of carbon offsets for the investment in projects that reduce emissions. A company that is not liable to pay carbon tax may implement an emission reduction project and register the project as a carbon project under the Clean Development Mechanism (CDM), Verified Carbon Standard (VCS) or Gold Standard (GS) [2].

The **carbon credits** are transferred to the South African registry and a company that is liable for carbon tax may purchase the carbon credits in tonnes of CO₂-equivalent. The carbon offsets mechanism thus incentivises a variety of projects, including industrial EEMs, to reduce emissions [2].

Additional EE incentives, such as the ADF Green Energy Fund and MCEP are available [12, 13, 29, 82]. Qualifying criteria for the ADF Green Energy Fund are that the project should be renewable energy or EE project. Additional details can be found in the *Energy Efficiency 2015 Market Intelligence Report* and various other academic publications [12, 13, 29, 82].

Financing of EE through loans from financial institutions, such as the Nedbank Green Energy Fund, are also available. The IFC has partnered with Nedbank to introduce a Green Energy Fund of up to

US\$200 million for the funding of renewable energy projects.ⁱ The IFC and Absa are in collaboration to finance green projects in South Africaⁱⁱ. The loan of up to US\$150 million will be used to finance biomass and other renewable energy projects that will assist South Africa in reaching its greenhouse gas reduction targets.

Table 2-1 shows a high-level summary of the financial incentives discussed in this section. The detailed discussion of available incentives and their requirements are beyond the scope of this study. The magnitude of available EE incentives highlights the technical potential for industrial EE. The South African EE incentive landscape is constantly evolving [84] and should therefore be continually monitored to keep abreast of any changes in the incentives offered. For this study, the focus is placed on the most prominent EE tax incentive, namely Section 12L [11], to test the structured approach.

ⁱ Nedbank. "IFC, Nedbank partner to increase green financing." Nedbank.co.za <https://www.nedbank.co.za/content/nedbank/desktop/gt/en/news/corporate-and-investment-banking-news/press-releases/2021/ifc-nedbank-partner-to-increase-green-financing.html> (accessed Feb. 13, 2022)

ⁱⁱ IFC. "IFC and Absa Bank Partner on Africa's First Certified Green Loan to Support Green Energy Projects". IFC.org <https://pressroom.ifc.org/all/pages/PressDetail.aspx?ID=26334> (accessed Feb. 13, 2022)

Table 2-1: A high-level summary of South African energy efficiency incentives.

Incentive	Requirements	Benefit
Section 12B	Production of renewable electricity.	<ul style="list-style-type: none"> • A 50%-30%-20% depreciation over a three-year period for most of the methods. • In the case of electricity generation from photovoltaic solar energy of less than 1 MW, a deduction of 100% of the value of the solar power system as a depreciation expense in the year that the plant is brought into use.
Section 12I [12] [13]	<ul style="list-style-type: none"> • IPP projects that used improved EE and cleaner production technology. • Under “Major Divisions 3: Manufacturing in the Standard Industrial Classification (SIC 3) of All Economic Activities, 5th Edition or SIC 7th Edition. Section C: Manufacturing. • Any Greenfield project with a minimum investment in qualifying assets of R50 million. • Any Brownfield project with a minimum additional investment in qualifying assets of R30 million. • Only one single tax entity can apply for the incentive. 	A tax allowance of between 35% and 100% of the costs of new and unused manufacturing assets.
Section 12L [13] [11]	<ul style="list-style-type: none"> • Non-renewable EE projects. • No concurrent benefit received from a government agency. • Independent M&V team. 	A tax deduction of 95c/ kWh of quantified EE.
Carbon credits	<ul style="list-style-type: none"> • Dependant on the offsets mechanism under which the project is registered. 	Benefits determined by offsets mechanism under which the project is registered.

Incentive	Requirements	Benefit
ADF Green Energy Fund ⁱ	<ul style="list-style-type: none"> • Renewable energy or EE projects. • A maximum of 200% increase in production capacity for expansion products. • Total investment cost not higher than 25% of the facility (capped at R250 million per project). • Maximum payback based on energy savings of 8 years. Minimum investment period of 3 years.	Loan with normal risk pricing with a cap of Prime + 1.6% or an equivalent fixed rate.
MCEP ⁱⁱ	<ul style="list-style-type: none"> • Only applicable to manufacturers under Standard Industrial Classification Code 3. • Applicant may not contemplate workforce reductions during the term of the facility. • Applicant will be required to achieve BBBEE Level 4 within 24 months. • Only applicable to Black Industrialists' businesses. • MCEP funds are blended at a leverage level of at least 20% funding from IDC. • Pre and post Business Development provided at a maximum of R3 million per applicant. • Limited to R50 million per applicant. 	Priced at a fixed rate of 4%. No fees apply.
Nedbank Green Energy Fund	Renewable energy projects.	To be announced.
Absa Green Loan	Biomass and other renewable energy projects.	To be announced.

ⁱIDC. "AFD Green Energy Fund." IDC.co.za. <https://www.idc.co.za/afd-green-energy-fund> (accessed Nov. 3, 2021).

ⁱⁱMCEP. "About MCEP." MCEP.co.za. <http://mcep.co.za/about/> (accessed Nov. 3, 2021).

2.3 Review of feasibility criteria

There are various factors that need to be included in the study of project feasibility to ensure all aspects are addressed [62]. A comprehensive assessment of various factors is critical to ensure a valid conclusion on the viability of the proposed project [62].

Gu *et al.* [61] suggested that the technical feasibility, economic feasibility, operational feasibility, and schedule feasibility be evaluated to minimise project risk. Cleland *et al.* [62] recommend that the technical, financial, legal, operational, and schedule requirements be evaluated to determine project viability. Elbok *et al.* [85] found that financial, technical, and strategic criteria are critical to the successful implementation of a project.

It is evident that there is variation in the scope and classification of feasibility criteria in literature. Technical and financial requirements are, however, cited as important by all the sources. Since the emphasis of this dissertation is on the utilisation of financial and technical feasibility criteria, **Technical** and **Financial** feasibility categories were chosen to evaluate the literature. A short description of each category is provided [61, 62, 85]:

- *Technical* criteria: the practicality of the proposed project, the integration capability to the existing system, the availability of technology and expertise, and the timeframe of the project.
- *Financial* criteria: analyses of the cost versus the associated benefits of a project.

The categories described above may be comprised of various individual evaluation criteria that need to be considered to determine if the feasibility requirements are met. A detailed literature review was conducted to determine what evaluation criteria constitute each of the categories. Multiple literature sources evaluating the feasibility of industrial EEMs were consulted. Criteria influencing the project feasibility were compiled and categorised according to the two categories above, namely *Technical* and *Financial* criteria.

The results of the literature review are presented in the following sections according to category. The *Technical* and *Financial* categories are discussed in Section 2.3.1 and Section 2.3.2, respectively. Each section provides a short description of each criterion under the relevant category. Additionally, an analysis of each criterion is provided by considering the percentage of sources that reference the criterion.

2.3.1 Technical criteria

Various technical criteria were compiled from the reviewed literature. The criteria are defined in Table 2-2 with an indication of the literature sources that reference each criterion.

Table 2-2: Descriptions of the technical criteria referenced by the reviewed literature.

Criterion	Description	Sources
<i>Energy savings</i>	An estimation of the energy saved as a result of the implementation of the EEM [86]. It is an indication of the technical performance of the EEM.	[64, 66-68, 70-77, 80, 86-88]
<i>Greenhouse gas (GHG) reduction potential</i>	The quantifiable reduction in CO ₂ -equivalent emissions as a result of the implementation of the EEM [86].	[66-68, 70-72, 74, 77-80, 86-90]
<i>Maturity of technology</i>	Mature technology refers to technology that has been in use for a long time and most of its initial or inherent problems have been reduced or resolved. Mature technology usually has established and wide-spread use [79].	[75, 76, 78, 79, 86, 91, 92]
<i>Reliability</i>	The capacity of the EEM to perform as designed and its resistance to failure [79].	[78, 79, 86-88, 91, 92]
<i>Production risk</i>	The severity and likelihood of production being negatively influenced due to the implementation of the EEM [44].	[44, 52, 93]
<i>Achievable EE</i>	An estimation of the performance of the EEM by determining the energy use before and after the implementation of the EEM, to the output obtained [4-6].	[65, 78, 79, 91, 92, 94]
<i>Availability of skills</i>	The availability of existing or easily acquired skills for the implementation, operation, and maintenance of the EEM [87]. It refers to the level of training that would have to be provided to personnel to successfully implement and maintain the EEM.	[66, 78, 87, 88, 93]
<i>Availability of knowledge</i>	The availability of in-house or local knowledge of the proposed EEM as well as the system that it is to be implemented on [44]. The criterion refers to the knowledge available for both the implementation and maintenance of the EEM.	[44, 66, 88, 93]

Criterion	Description	Sources
<i>Compatibility</i>	The degree of compatibility that the EEM shows to existing infrastructure. It refers to the level of adjustments that would have to be made to existing infrastructure to accommodate the implementation of the EEM [66].	[66, 67, 92, 94]
<i>Maintenance</i>	The degree of maintenance that the EEM will require throughout its lifetime [89]. The regularity and complexity of the required maintenance should be considered for both the EEM as well as the system on which it is implemented.	[66, 89, 94]
<i>Safety</i>	The level of danger during implementation, operation, and maintenance of the proposed EEM [79].	[78, 79, 89]
<i>Implementation time</i>	The duration of time to implement the EEM [66].	[65, 66]
<i>Ease of implementation</i>	The level of technical and logistical difficulty in executing the project scope of the EEM [85]. EEMs that are dependent on the implementation of other EEMs, or are part of a larger project, have a higher level of complexity than standalone projects.	[65, 66]
<i>Remaining equipment lifetime</i>	The age of existing equipment that is either retrofitted or replaced by the EEM. Some equipment can only be replaced at the end of their lifetime [52].	[52, 66]
<i>Space required</i>	An assessment of the availability of space for the implementation of the EE. It includes the difficulty of the procurement of additional land required [79].	[78, 79]
<i>Climate</i>	The influence of the location climate on the technical performance of the EEM. For example, higher altitude levels can lead to an increased pressure drop over equipment [66].	[66]
<i>Automation grade</i>	The level of human input required for the operation of the EEM after implementation.	[78]
<i>Spare parts availability</i>	The availability of spare parts for preventative and corrective maintenance [92].	[92]

Figure 2-2 shows a summary of the percentage of sources from the review that refer to the technical criteria described in Table 2-2. The criteria are sorted in descending order according to the percentage of studies that refer to each criterion.

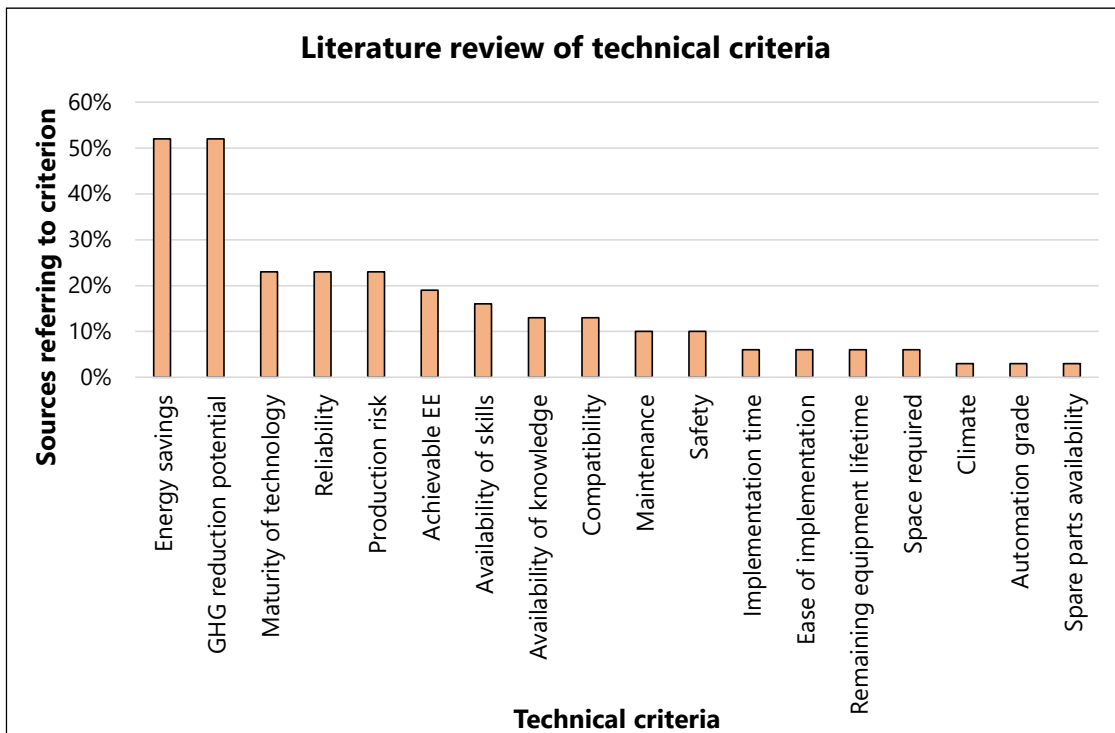


Figure 2-2: The percentage of sources referring to each technical criterion.

Figure 2-2 shows that the potential *Energy savings* and the *GHG reduction potential* are the most referenced technical criteria with 52% of the sources referring to each of the criteria. The *Maturity of technology*, *Reliability* and *Production risk* criteria are referred to in 23% of the reviewed sources. *Achievable EE* is referenced in 19% of the reviewed sources while 16% of the reviewed sources refer to the *Availability of skills* criteria.

Availability of knowledge and *Compatibility* are referenced in 13% of the sources. *Maintenance* and *Safety* criteria are mentioned in 10% of the reviewed sources. *Implementation time*, *Ease of implementation*, *Remaining equipment lifetime*, *Space required*, *Climate*, *Automation grade*, and *Spare parts availability* are present in less than 10% of the reviewed sources.

The review of the technical criteria illustrated that there are several technical criteria to consider during the feasibility assessment of EEMs. To add structure to the evaluation of the magnitude of technical criteria, similar criteria are grouped. Two overarching themes of technical criteria that emerged from the literature review are the **Performance** of the EEMs and the **Complexity** of the EEMs.

The **Performance** of an EEM is related to the quantifiable output of the successful implementation of the measure [22]. Since the *Energy savings*, *GHG reduction potential*, and *Achievable EE* are quantifiable indicators of the performance of an EEM, they were grouped under the *Performance* category.

Complexity is defined as the several interconnecting parts that constitute a project [95]. The remainder of the technical criteria from the review are related to the complexity of implementing and maintaining an EEM. The *Complexity* category is further decomposed into subcategories that relate the overall complexity to specific focus areas.

Compatibility with existing infrastructure, *Remaining lifetime of equipment*, *Spare parts availability*, *Space required* for equipment, and the effect of the *Climate* on equipment performance are factors related to the complexity of equipment. Therefore, the criteria were grouped under the *Equipment* complexity category.

Ease of implementation and *Implementation time* relate to the complexity of implementing the EEM. Therefore, they were grouped under the *Implementation* complexity category. The *Availability of knowledge* and *Availability of skills* criteria were grouped under the *Knowledge and Skills* complexity category.

The *Maturity of technology*, *Production risk*, and *Reliability* criteria describe the technical risk contributing to the complexity of an EEM. They were therefore grouped under the *Technical risk* category. *Maintenance*, *Safety*, and *Automation grade* affect the daily operations of the system upon which an EEM is implemented. They were thus grouped under *Operational* complexity.

Figure 2-3 shows the categorisation of the technical criteria from the literature review. Grouping of the technical criteria will assist with the design of the structured approach in Section 2.6. The grouped *Technical* criteria are used to weight the criteria via questionnaire in the technical feasibility assessment of Section 2.6.1 as well as the prioritisation hierarchy of Section 2.6.2. The weighted criteria are subsequently used to prioritise the EEMs using the Analytical Hierarchy Process (AHP). Additional detail is provided in Section 2.6.

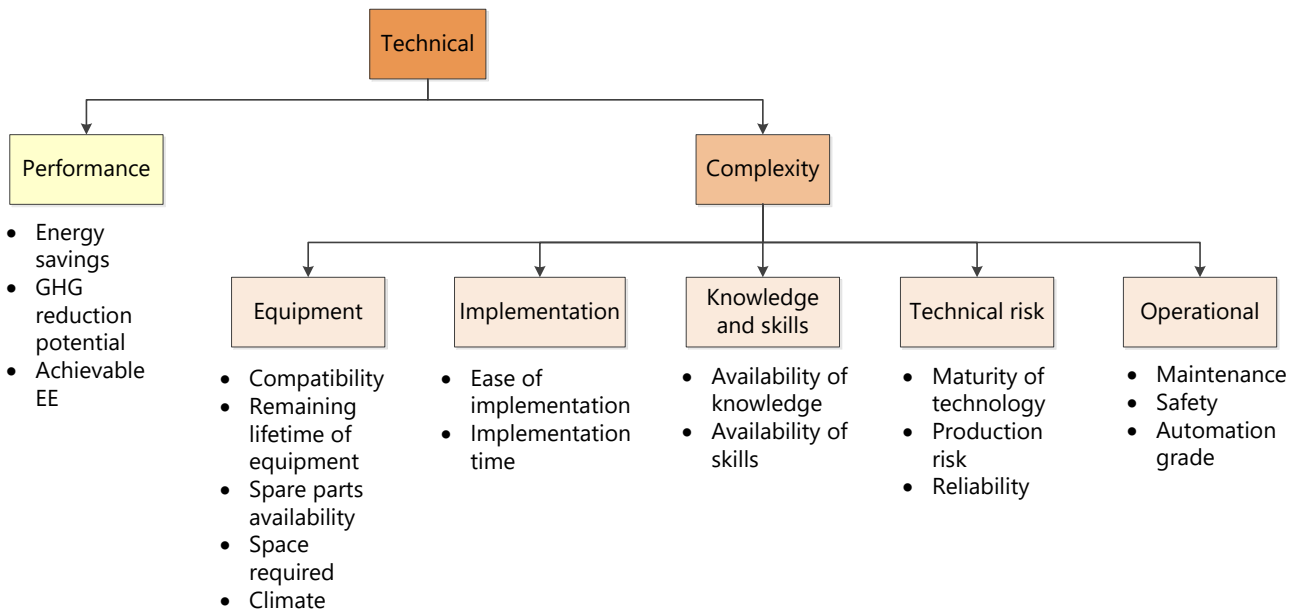


Figure 2-3: The categorisation of the *Technical* feasibility criteria.

2.3.2 Financial criteria

Various financial criteria were compiled from the reviewed literature. The criteria are defined in Table 2-3 with an indication of the literature sources that reference each criterion.

Table 2-3: Descriptions of the financial criteria referenced by the reviewed literature.

Criterion	Description	Sources
<i>Implementation cost</i>	The total cost to implement the EEM, including the capital cost (absolute cost) [85].	[6, 63, 66, 67, 70-72, 74, 75, 78-80, 88, 92-94]
<i>Payback period (PP)</i>	The amount of time to recover the implementation cost of the EEM [85].	[6, 66, 74, 76, 78-80, 86, 88, 89, 91, 92, 96]
<i>Cost savings</i>	The monetary cost savings as a result of implementing the EEM [52]; for example, reduced fuel demand leading to lower operational costs.	[6, 44, 52, 63, 75, 80, 86, 88, 89, 91, 93]
<i>Cost of saved energy</i>	The ratio of the total annualised cost of implementing and operating an EEM to the annual potential energy saved as a result of the measure, i.e. the annual cost of saving one unit of energy [69, 86].	[64, 67-69, 71-73, 75, 77, 86]
<i>Energy price</i>	The cost of procuring one unit of energy [69, 77].	[44, 52, 69, 77-79, 87, 88, 93, 94]

Criterion	Description	Sources
<i>Net present value (NPV)</i>	The difference between the present value of the cash inflows and the cash outflows [85].	[6, 66, 76, 78, 79, 88, 89, 96]
<i>Operation and maintenance (O&M) costs</i>	The costs related to the operation and maintenance of the implemented EEM [66].	[66, 70, 72, 74, 78, 79, 92, 96]
<i>Internal rate of return (IRR)</i>	The discount rate that yields a zero NPV of all cash flows for the considered EEM [85].	[6, 76, 78, 89, 96]
<i>Incentives</i>	The availability of qualifying incentives for the EEM such as tax incentives and government funding [10].	[44, 52, 80, 93]
<i>Exchange rate risk</i>	The likelihood of the change in the exchange rate of equipment or services purchased in a currency different from the country where the EEM is implemented [88].	[88, 89, 94]
<i>Rate of return (ROR)</i>	The ratio of the average financial benefit expected to the initial investment amount [85].	[63, 66]
<i>GHG abatement cost</i>	The ratio of the equivalent annual investment cost to the GHG emission reduction potential, i.e. the annual cost of saving one tonne of CO ₂ -equivalent (cost per unit) [68].	[68, 71]
<i>Annualised lifecycle cost (ALCC)</i>	An estimation of the total costs, including implementation, operating, and maintenance costs over the lifetime of the EEM [90].	[89, 90]
<i>CO₂ price</i>	The cost per tonne of CO ₂ -equivalent emitted, including taxes such as Carbon tax [77].	[77]
<i>Profitability index (PI)</i>	The ratio of the payoff to the investment of the EEM [96].	[96]

Figure 2-4 shows a summary of the percentage of sources from the review that refer to the financial criteria described in Table 2-3. The criteria are sorted in descending order according to the percentage of studies that refer to each criterion.

Figure 2-4 shows that *Implementation cost*, *PP*, and *Cost savings* are the top three most referenced financial criteria with 48%, 39%, and 35% of the sources referring to the respective criteria. *Cost of saved energy* is referred to in 32% of the reviewed sources while 29% of the reviewed sources refer to the *Energy price*. Furthermore, 26% and 23% of the reviewed sources refer to the *NPV* and *O&M costs*, respectively. *IRR*, *Incentives*, and *Exchange rate risk* are cited in 16%, 13% and 10% of the

sources, respectively. *ROR*, *GHG abatement cost*, *ALCC*, *CO₂ price*, and the *PI* are mentioned in fewer than 10% of the reviewed sources.

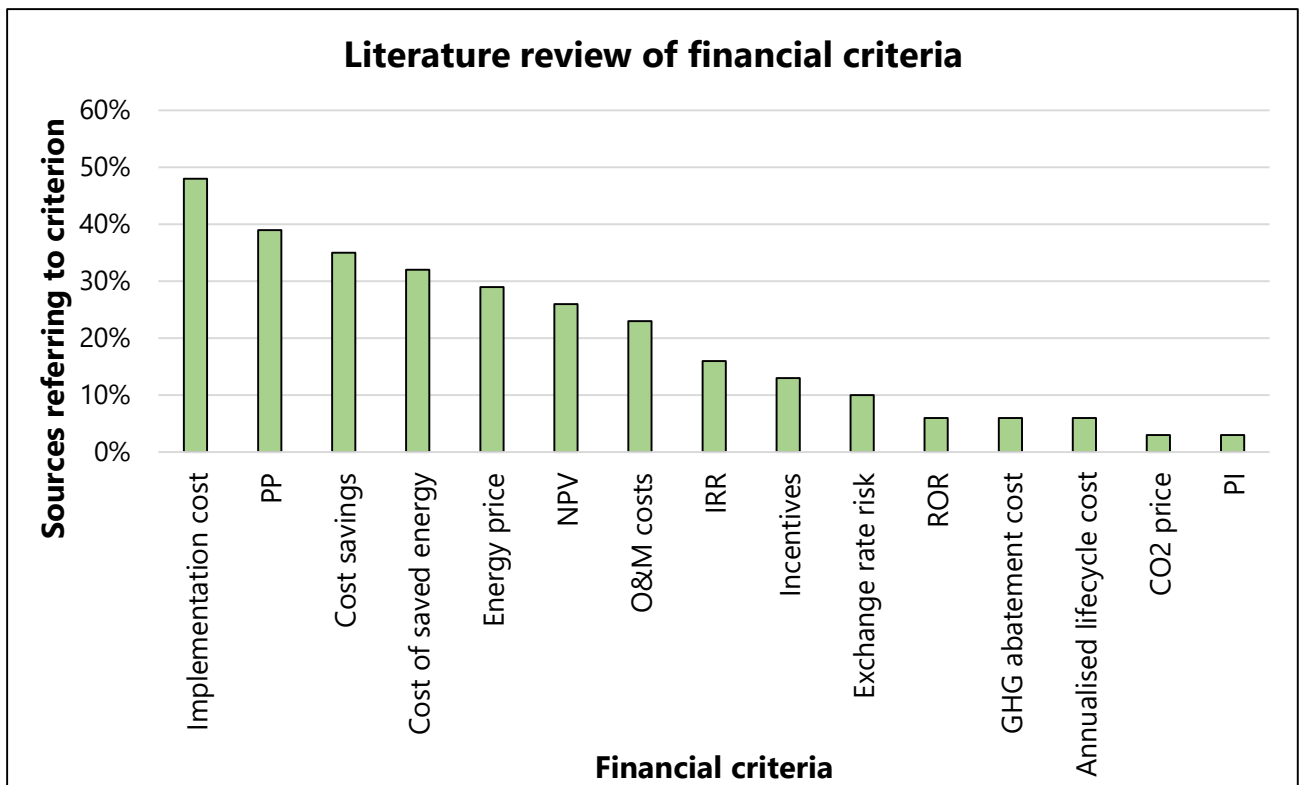


Figure 2-4: The percentage of sources referring to each financial criterion.

The review of the financial criteria illustrated that there are several criteria to consider during the financial feasibility assessment of EEMs. Although many of the financial criteria have interactions with one another, each criterion influences the feasibility of EEMs separately. Therefore, each criterion is considered independently.

Financial feasibility assessments can be separated into two distinguished analyses, namely profitability analyses and financial analyses [97]. The profitability analysis involves an assessment of the likelihood of the project to turn a profit. Financial analysis includes an assessment of the project benefits and costs, as well as external factors that may influence the project economics [97].

To add structure to the evaluation of the magnitude of financial criteria, similar criteria were grouped with the two themes of financial feasibility analysis, namely profitability analyses and financial analyses, used as a guideline. Since profitability analysis evaluates the likelihood of the project to turn a profit, **Profitability** was chosen as one of the categories. Financial analysis evaluates the project costs and benefits associated with the costs, and therefore **Cost**, and **Benefits** were chosen as categories. Financial analysis further includes external factors beyond the control of the company

and therefore **External** was selected as a category. The financial feasibility criteria from the review were thus grouped according to the following categories: **Profitability**, **Cost**, **Benefits**, and **External**.

ROR, *PP*, *NPV*, *IRR*, and *PI* are indicators of the profitability of the EEMs [97] and are therefore grouped under **Profitability**. *Implementation cost*, *O&M costs*, *Cost of saved energy*, *GHG abatement cost*, and *ALCC* were grouped under **Cost** since these criteria are related to the cost of implementing and maintaining an EEM.

Incentives and *Cost savings* were classified as **Benefits** related to the implementation of an EEM. External criteria such as *Energy price*, *Exchange rate risk*, and *CO₂ price* are beyond the control of the company and may influence the financial analysis of the EEMs. Thus, they were grouped under the **External** category.

Figure 2-5 shows the categorisation of the financial criteria described above. Grouping of the financial criteria will assist with the design of the structured approach in Section 2.6. The grouped *Financial* criteria are used in the prioritisation hierarchy of Section 2.6.2 to weight the criteria via questionnaire. The weighted criteria are subsequently used to prioritise the EEMs using the AHP. Additional detail is provided in Section 2.6.

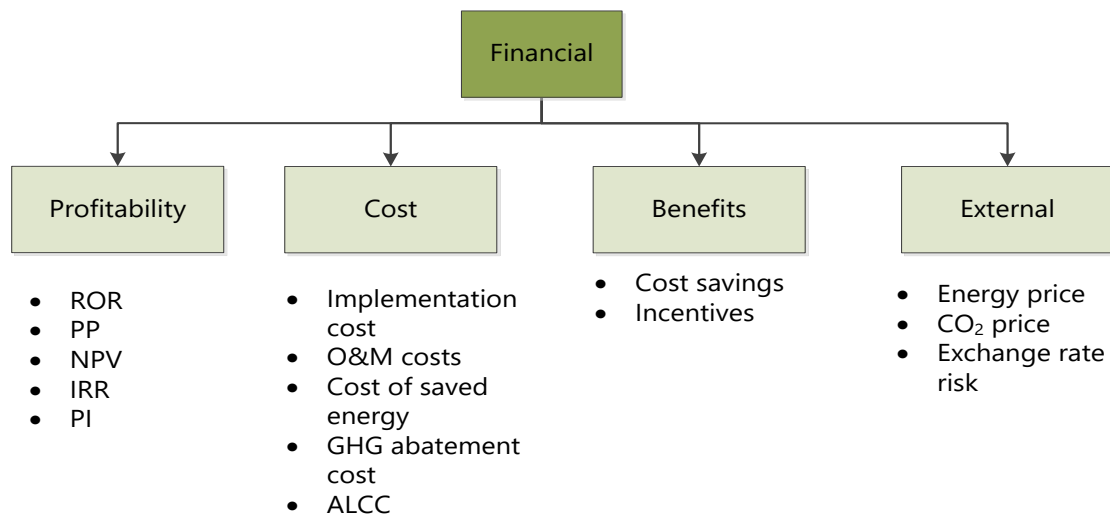


Figure 2-5: The categorisation of the *Financial* feasibility criteria.

2.4 Selection of prioritisation criteria

Project prioritisation is an important tool utilised for project management. The scope of prioritisation criteria utilised for project prioritisation varies greatly, since organisations may differ in opinion on which criteria are important [98]. Literature was consulted to gain an understanding of which criteria are commonly considered in project prioritisation.

Various studies have prioritised energy projects based solely on cost [69, 72, 73, 75, 77, 86]. However, several studies have prioritised energy projects based on multiple criteria. Svensson *et al.* [65] prioritised EEMs in industrial production systems by evaluating project complexity and the effect of the EEM.

Mokhtar *et al.* [66] considered a variety of qualitative and quantitative criteria in their selection of EEMs for the cement industry. Qualitative criteria include implementation possibility, adjustment level with existing equipment, operator skill required, and disruption time for project execution. Quantitative criteria include energy savings, investment costs, and PP.

UNIDO [75] quantified and prioritised EEMs for Chinese industrial steam systems by considering the cost of conserved energy, energy savings, implementation cost, CO₂ reduction potential, and cost savings. McKinsey & Company [99] ranked industrial energy projects according to GHG reduction potential and GHG abatement cost.

Contreras *et al.* [78] utilised four categories of criteria for the prioritisation of industrial energy management projects, namely economic, environmental, social, and technical criteria. Economic criteria considered by Contreras *et al.* [78] include investment cost, O&M costs, equivalent annual cost, NPV, IRR, fuel cost, and fuel availability. Contreras *et al.* [78] considered emission reduction and land use under the environmental criteria category. Social criteria considered by Contreras *et al.* [78] include social acceptability, job creation, and safety. Technical criteria considered by Contreras *et al.* [78] consist of EE, automation grade, operability and reliability, and maturity of technology.

Elbok *et al.* [85] evaluated projects for portfolio selection based on strategic, financial, and technical criteria. Strategic criteria include environmental benefits, social benefits, and market potential. Financial criteria considered by Elbok *et al.* [85] include total cost investment and operating costs, IRR, NPV, PP, ROI and ROR. Project complexity, time involved, and degree of innovation are some of the criteria considered under the technical criteria category.

Algarin *et al.* [92] reviewed technical, economic, social, environmental, and risk criteria for their evaluation of renewable energy sources. Technical criteria included EE, maturity of technology, spare parts availability, infrastructure, and reliability. Investment costs, O&M costs, PP, and service life were considered as part of the economic criteria. Social criteria include acceptability by local residents and local job creation. Environmental criteria include gas emissions and land requirements while the risk criteria included climate conditions and investment risk.

The literature review of frequently used project prioritisation criteria highlights that a variety of criteria is used for project prioritisation. However, common themes of criteria are evident from the literature review, namely technical, financial, and environmental categories. The focus of this dissertation is on the technical and financial feasibility and thus the environmental category was disregarded.

There is a clear overlap between the technical and financial feasibility criteria reviewed in Section 2.3 and common prioritisation criteria discussed in Section 2.4. The feasibility criteria reviewed in Section 2.3 that also occur in the literature review of the prioritisation criteria are shaded in green in Table 2-4.

Table 2-4: An overlap between the feasibility criteria and prioritisation criteria for industrial EEMs.

Feasibility criterion	Prioritisation criteria literature
<i>Energy savings</i>	[66, 75]
<i>GHG reduction potential</i>	[66, 75, 78, 99]
<i>Maturity of technology</i>	[78, 92]
<i>Reliability</i>	[78, 92]
<i>Production risk</i>	[66]
<i>Achievable EE</i>	[78, 92]
<i>Lifetime of measure</i>	[78, 92]
<i>Availability of skills</i>	[66, 78]
<i>Availability of knowledge</i>	[66]
<i>Compatibility</i>	[66, 92]
<i>Maintenance</i>	[66]
<i>Safety</i>	[78]
<i>Implementation time</i>	[66, 85]
<i>Ease of implementation</i>	[66, 85]
<i>Remaining equipment lifetime</i>	[66]
<i>Space required</i>	[78]
<i>Climate</i>	[66]
<i>Automation grade</i>	[78]
<i>Spare parts availability</i>	[92]
<i>Implementation cost</i>	[65, 66, 69, 72, 73, 75, 77, 78, 85, 86, 92]
<i>PP</i>	[66, 78, 85, 92]

Feasibility criterion	Prioritisation criteria literature
<i>Cost savings</i>	[75]
<i>Cost of saved energy</i>	[75]
<i>Energy price</i>	[78]
<i>NPV</i>	[66, 78, 85]
<i>O&M costs</i>	[66, 78, 85, 92]
<i>IRR</i>	[78, 85]
<i>Incentives</i>	
<i>Exchange rate risk</i>	
<i>ROR</i>	[66, 85]
<i>GHG abatement cost</i>	[99]
<i>ALCC</i>	
<i>CO₂ price</i>	
<i>PI</i>	

Table 2-4 shows that 85% of the feasibility criteria from Section 2.3 are used as prioritisation criteria in the literature of Section 2.4. Only five of the mentioned feasibility criteria, marked in orange in Table 2-4, were not considered a priority by the literature sources. Thus, there is significant overlap between the feasibility criteria and the prioritisation criteria from the respective literature reviews. Therefore, Table 2-4, clearly verifies the feasibility criteria reviewed in Section 2.3 as the prioritisation criteria for industrial EEMs.

2.5 Selection of prioritisation technique

Numerous project prioritisation techniques are available to enable decision makers to make an informed decision. These prioritisation techniques range from simple single-criterion techniques, such as using project implementation cost, to detailed multi-criteria decision-making (MCDM) techniques. Since various criteria should be taken into consideration when determining the order of project implementation, MCDM techniques should be utilised [100, 101].

Common MCDM prioritisation methods used in the energy field include the Weighted Sum Method (WSM); Weighted Product Method (WPM); Analytical Hierarchy Process (AHP); Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method; elimination et choix traduisant la réalité (ELECTRE) method; and the Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE) method [100, 101].

A comprehensive analysis of the numerous MCDM techniques available is beyond the scope of this study. A short description of common MCDM techniques in the energy field is provided in Appendix B.1.

The AHP is one of the most common utilised prioritisation techniques for the evaluation of energy projects [85, 102]. The AHP method is scalable and can easily be adjusted in size due to its hierarchal structure [100]. The AHP method was chosen as the preferred prioritisation technique due to its prevalence in prioritising EEMs and its ability to simplify the decision-making process by deconstructing conflicting criteria into a hierarchy [101].

The AHP aims to define the optimum alternative by categorising alternatives regarding the criteria that describe them [101]. The application of AHP to a decision problem involves five steps [103]. The five steps are illustrated in detail in Appendix B.2. A summary of the five steps is given in the subsections that follow.

Step 1: Hierarchical structuring of the decision problem

The first step is the structuring of the decision problem into a hierarchical model. Elements of the decision problem are grouped based on common characteristics and formulated into a hierarchy with different levels. A simple AHP model is shown in Figure 2-6 and has three levels, namely the goal, the criteria and the alternatives [103].

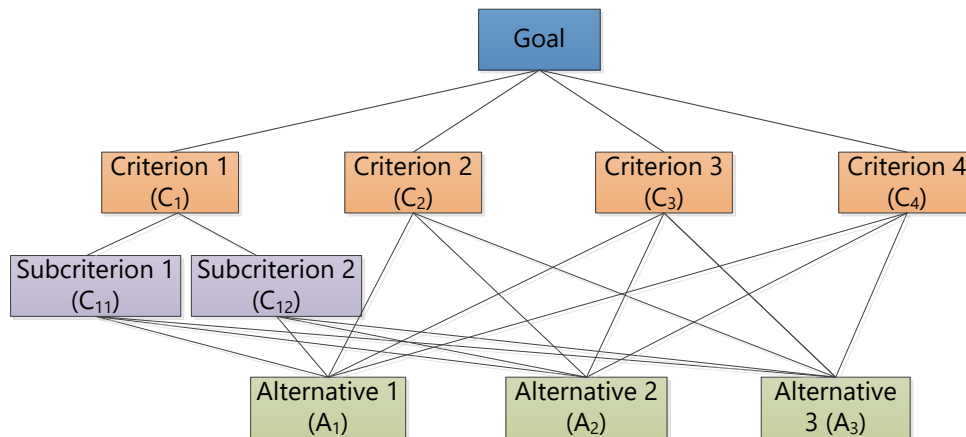


Figure 2-6: A simple AHP model with the goal, criteria, subcriteria, and alternatives.

The goal is the desired outcome from applying the AHP. The criteria are weighted according to their contribution to reaching the goal and can be further divided into subcriteria. The simple AHP model can, however, be adapted with more levels to accommodate more complex decision-making problems, with the addition of more subcriteria as illustrated in Figure 2-7.

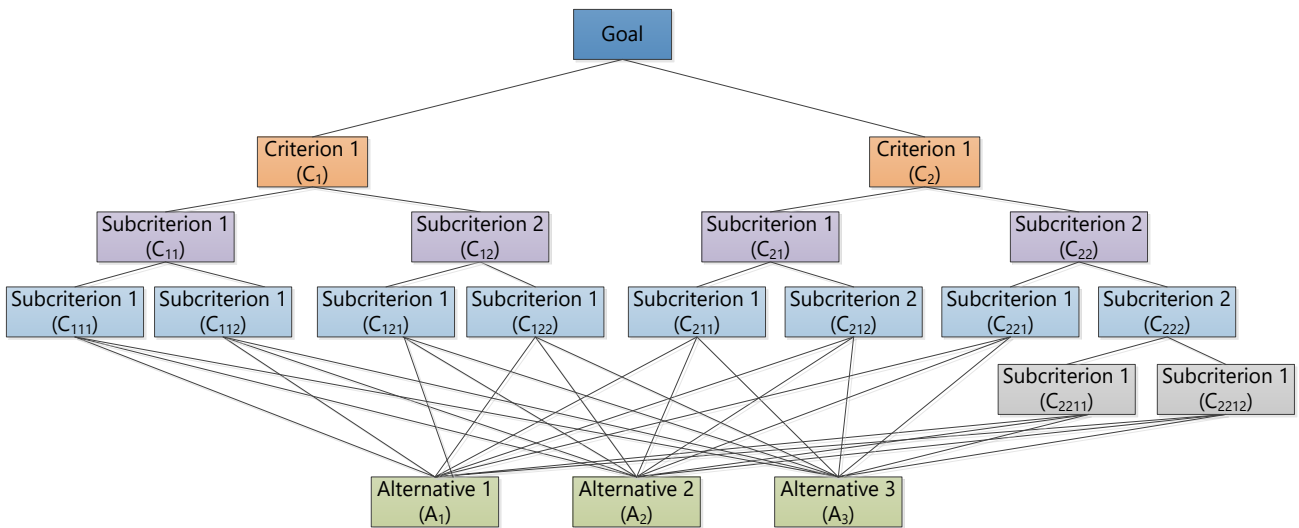


Figure 2-7: A more complex AHP model (extension of Figure 2-6).

The number of criteria that can be compared and judged simultaneously without error is 7 ± 2 [104]. Therefore, it is encouraged to group similar criteria so that the number of criteria per level in the hierarchy does not exceed nine.

Step 2: Pair-wise comparisons and the judgement matrix

The second step of the AHP involves pair-wise comparisons to obtain a judgement matrix. The elements of a particular level (child element) are compared with respect to the element in the immediate upper level (parent element).

Table 2-5 shows a scale of relative importance from 1 to 9 that is used to conduct pair-wise comparisons of the elements [105]. An element receiving a higher rating with respect to another element is considered more important by the decision maker.

Table 2-5: The comparison scale for the AHP [105].

Intensity of Importance	Definition
1	Equal importance
2	Slightly more important
3	
4	Moderately more important
5	
6	Strongly more important
7	
8	Extremely more important
9	

The pair-wise comparisons are captured in the form of judgement matrices. Each entry of the judgement matrix is governed by three rules, illustrated in Equation (1) to Equation (3) where a_{ij} refers to element i compared to element j .

$$a_{ij} > 0 \tag{1}$$

$$a_{ij} = \frac{1}{a_{ji}} \tag{2}$$

$$a_{ii} = 1 \tag{3}$$

Equation (1) states that all entries in the judgmental matrix should be positive. Equation (2) is known as the reciprocity rule where the reciprocal score of a judgment is entered in the transpose position of the judgmental matrix. Equation (3) states that the diagonal of the judgmental matrix is one since the importance of a criteria relative to itself is equal [106].

An illustration of the pair-wise comparisons of the criteria is shown in Figure 2-8. Criterion 1 is individually compared to each of the other three criteria, as shown by the blue lines in Figure 2-8. Thereafter, Criterion 2 is individually compared to Criterion 3 and Criterion 4, as shown by the yellow lines in Figure 2-8. Finally, Criterion 3 is compared to Criterion 4, as shown by the green lines in Figure 2-8.

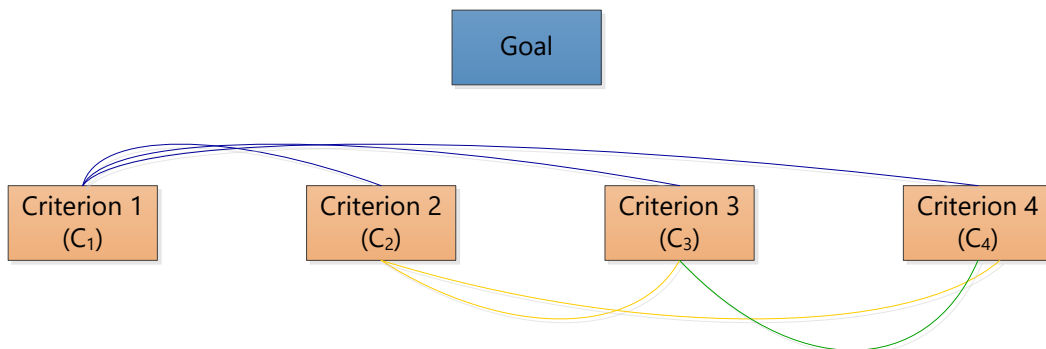


Figure 2-8: Illustration of the pair-wise comparison of elements on one level of the hierarchy.

The completion of the judgement matrix is illustrated by Table 2-6. Criterion 1 is first compared to Criterion 2 to determine which criterion is more important. If Criterion 1 is rated as more important than Criterion 2, a chosen score from Table 2-5 is entered in the corresponding position of the matrix, as shown in dark blue in Table 2-6. Simultaneously, the reciprocal value is assigned in the transpose position as shown in light blue in Table 2-6. Criterion 1 is subsequently individually compared to

Criterion 3 and Criterion 4 and the assigned scores are entered in the judgement matrix, as shown in Table 2-6.

Table 2-6: Illustration of completing the judgement matrix for the elements on a hierarchy level.

	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Criterion 1	1	3	2	4
Criterion 2	1/3	1		
Criterion 3	1/2		1	
Criterion 4	1/4			1

The rest of the judgement matrix is completed by conducting pair-wise comparisons between Criterion 2, Criterion 3, and Criterion 4 in the same manner described above.

Step 3: Consistency and weighting of criteria

After the judgement matrices have been obtained, the local weights of each element can be calculated. The local weights are calculated using the approximated eigenvector method where the entries in each row of the judgement matrix are multiplied and the n^{th} roots of each product is calculated where n is the number of elements of the judgement matrix [105].

The n^{th} roots are subsequently summed, and the resulting value is used to normalise the values to add up to one. The normalised vector is a good approximation for the eigenvector and is indicative of the local weights for each element in the associated judgement matrix. The approximated eigenvector method is explained and illustrated in detail in Appendix B.2.

The respective child criteria under each parent criterion of the hierarchy should sum to one to verify that the local weights were assigned correctly. This is illustrated by way of an example in Figure 2-9 where the local weights of both the second level in the hierarchy (shown in orange) and the third level in the hierarchy (shown in purple) sum to one.

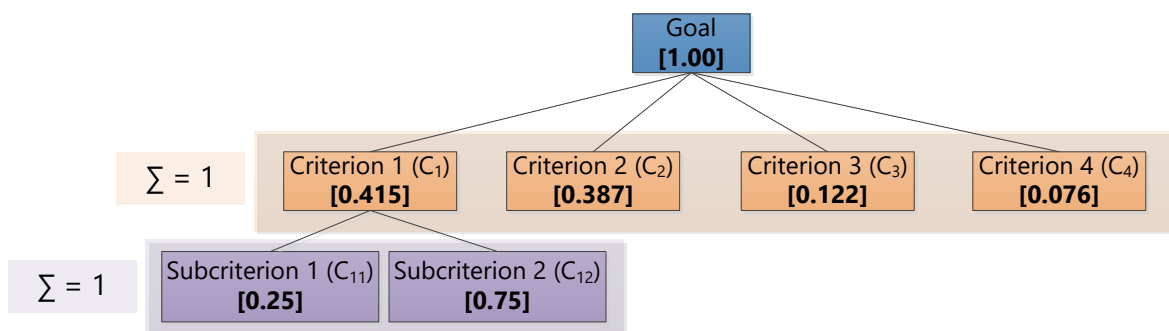


Figure 2-9: The local weights of the child criteria under a parent criterion sum to one.

The global weights of each criterion and subcriterion with respect to the goal are calculated by multiplying its local weight with the local weight of its parent element as shown in blue in Figure 2-10.

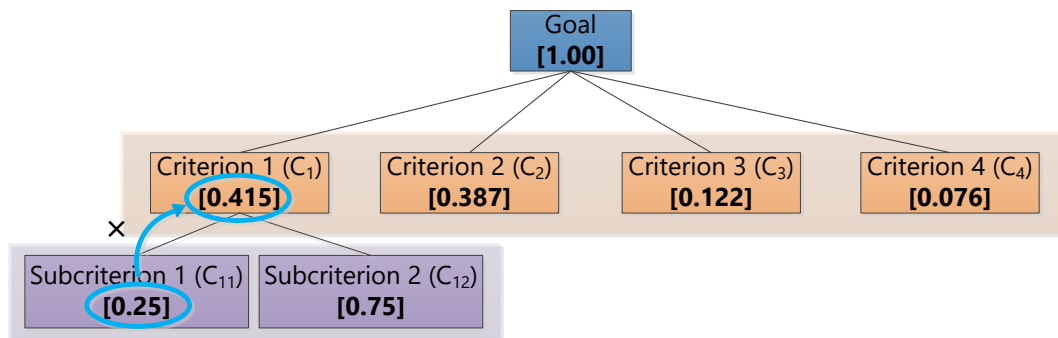


Figure 2-10: The calculation of the global weight of a criterion from the local weights.

It is important to note that the weighting of criteria on each upper level will profoundly impact the final weights of the criteria on the lower level. Therefore, care needs to be taken to ensure that the scores assigned to individual criteria are representative of its true weight. To illustrate this phenomenon, consider the case above where Criterion 1 is assigned a much higher score than Criterion 4. Subcriterion 1 and Subcriterion 2 will have thus ultimately be weighted much heavier than any of the subcriteria under Criterion 4.

The global weights for the example in Figure 2-9 are shown in Figure 2-11. To confirm the accuracy of the global weight assignment, the child elements should sum to the global weight of the parent element as shown in Figure 2-11. The pink shading illustrates that the global weights of the Subcriterion 1 and Subcriterion 2 sum to the global weight of Criterion 1. The purple shading in turn shows that the global weights of the criteria sum to one, which is the global weight of the goal.

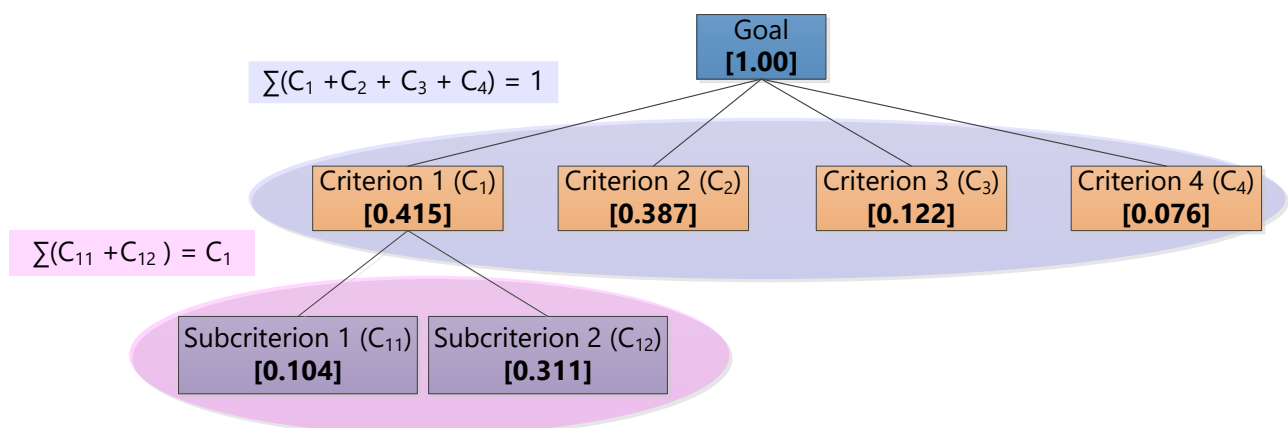


Figure 2-11: The global weights of the child criteria sum to the weight of the parent criterion.

Consistent judgements are critical during the decision-making process. Perfect consistency of the judgements made by the decision-maker is hard to comply with, since human judgements are involved based on verbal descriptions of the scale of importance [105]. Saaty [107] therefore proposed a consistency index (CI) to evaluate the consistency of the judgments made by the decision-maker as shown in Equation (4)

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

where λ_{max} is the maximum eigenvalue of the judgment matrix. The consistency index is subsequently used to calculate the consistency ratio (CR) as shown in Equation (5)

$$CR = \frac{CI}{RI} \tag{5}$$

where RI is the random index. The random index is the average of 500 randomly filled matrices which is available in published tables, such as the one presented in Table 2-7 [105]. n in Table 2-7 refers to the number of elements in the judgmental matrix. Consistency ratios of 0.1 or below are considered acceptable [105].

Table 2-7: Consistency indices for randomly generated matrices [105].

n	2	3	4	5	6
RI	0	0.58	0.9	1.12	1.24

Step 4: Local weights of the alternatives

The same method as described in Step 3 can be used to determine the local weights (eigenvectors) and consistency ratios for the judgement matrices that evaluate the alternatives with respect to each criterion. In the case of this dissertation, the alternatives are the EEMs that need to be prioritised.

However, the number of alternatives that can be compared and judged simultaneously without error is 7 ± 2 [104]. Thus, if the number of EEMs is more than nine, an excessive number of pair-wise comparisons would be required. In the case of more than nine EEMs, the method described in Step 3 may lead to errors in judgements [105]. Additionally, EEMs may frequently be added or removed from the list of projects to prioritise as more information regarding the feasibility thereof becomes available. This would result in a tedious and repetitive process every time the list of EEMs is amended.

To circumvent the issue of multiple comparisons and frequently changing alternatives, each EEM is given an absolute rating with respect to each criterion. If the criterion under consideration is

qualitative, **ratings scales** are used to assign a rating to each alternative with respect to the criterion. Ratings scales are developed for each criterion with a rating assigned to a variety of situations that may occur for the specific criterion. A scale with three, five, seven or ten different values is recommended [105]. The higher rating should reflect greater convenience with respect to the alternative [105].

An example of a ratings scale with three values for the evaluation of the *Maturity of technology* of a proposed EEM is shown in Table 2-8. The ideal situation for the *Maturity of technology* of a proposed EEM is that the EEM utilises mature technology that is widely used in the industry. Therefore, a rating of 3 is used for such a situation since a higher rating reflects a greater convenience.

Table 2-8: An example of a ratings scale for evaluating the *Maturity of technology* criterion.

Maturity of technology	Rating
New technology.	1
Mature technology that is not widely used or mature technology incorporating new features.	2
Mature technology that is widely used in the industry.	3

Since various ratings scales, each with a different scale, may be used for the various qualitative criteria to be evaluated, the weight of each EEM with respect to a criterion is calculated by normalisation. Thus, the weight of an EEM with respect to a criterion is calculated by dividing the rating assigned to that EEM by the sum of the ratings of all the EEMs.

For simplicity, ratings scales may also be used for quantitative criteria. However, the numerical value of a quantitative criterion with respect to an EEM is inherently indicative of its rating. Normalisation is required to calculate the local weights of the EEMs with respect to the quantitative criteria. This is done to allow comparison between different criteria since quantitative criteria may have different units of measure. Since a higher rating should reflect a greater convenience, different normalisation techniques are proposed for *benefit* criteria and *cost* criteria.

A high numerical value for a *benefit* criterion, such as *Energy savings*, is preferred to a lower numerical value. Therefore, high numerical values of benefit criteria should correspond to high normalised values, i.e. high local weights. The normalisation of *benefit* criteria is calculated by Equation (6)

$$n_{ij} = \frac{r_{ij}}{\sum_{i=1}^m r_{ij}} \quad (6)$$

where n_{ij} refers to the normalised rating (i.e. the local weight) of alternative i with respect to criterion j . r_{ij} refers to the numerical value of alternative i for criterion j and m refers to the number of EEMs [108].

A low numerical value for a *cost* criterion, such as *Implementation cost*, is preferred to a higher numerical value. Therefore, low numerical values of *cost* criteria should correspond to high normalised values (high local weights) since a higher score reflects greater convenience. The normalisation of *cost* criteria is calculated by Equation (7)

$$n_{ij} = \frac{\frac{1}{r_{ij}}}{\sum_{i=1}^m \frac{1}{r_{ij}}} \quad (7)$$

Step 5: Final weights of the alternatives

The local weights calculated in Step 4 are aggregated to obtain the final weights of each of the EEMs on the bottom level of the simple AHP model shown in Figure 2-6. The final weight of each alternative, i.e. each EEM, is calculated by Equation (8)

$$\text{Final weight of } A_i = \sum_{j=1}^k (n_{ij} \times w_j) \quad (8)$$

where A_i refers to alternative i ; n_{ij} is the normalised score (local weight) of alternative i with respect to criterion j ; w_j is the global weight of criterion j ; and k is the total number of criteria. With the global weight of each EEM known, the EEMs can be prioritised according to descending final scores.

Summary

A summary of the five steps used to prioritise alternatives is presented in Figure 2-12.

Step 1 is to structure the decision problem into a hierarchy with the goal, criteria, subcriteria, and alternatives. **Step 2** involves pair-wise comparisons of the criteria under each parent criterion and the construction of judgment matrices.

Step 3 is the calculation of the local and global weights of each criterion. The consistency ratios for the judgment matrices are then calculated. **Step 4** is the assignment of local weights to each EEM by normalisation. For quantitative criteria, the numerical values are normalised. For qualitative criteria, ratings are assigned according to ratings scales and then normalised.

Step 5 is the calculation of the final weights of each EEM: the normalised local weight of the EEM with respect to the criterion is multiplied by the global weight of the criterion. This is repeated for all the criteria and the respective answers are summed to obtain the final weight of the EEM. The EEMs can then be prioritised according to their final scores.

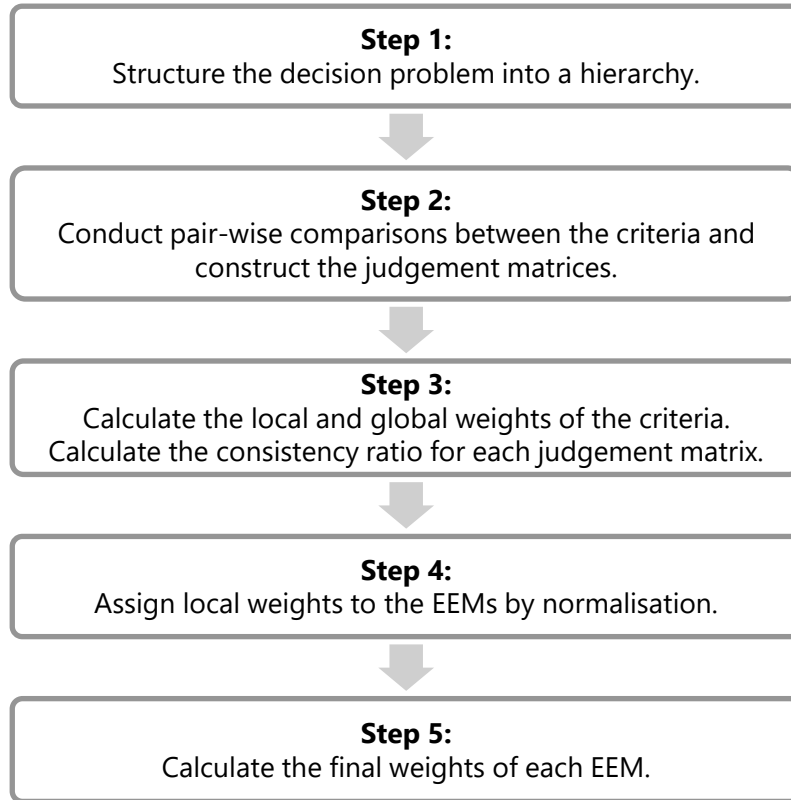


Figure 2-12: A summary of the five steps for prioritisation of EEMs with the AHP.

Section 2.5 aims to give a brief overview of the AHP. The AHP is specifically applied to this study in Section 2.6.

2.6 Design of the structured approach

Following the comprehensive review of literature for the selection of incentives (Section 2.2), feasibility criteria (Section 2.3), prioritisation criteria (Section 2.4), and prioritisation techniques (Section 2.5), the structured approach is designed in this section.

The need to evaluate multiple EEMs in a structured and systematic manner is one of the requirements of the research objective stated in Section 1.4. A structured approach is one that reaches a solution for the stated problem in an organised manner [12]. In the case of this dissertation, the problem is that it is a difficult and time-consuming process to evaluate feasibility and prioritise multiple EEMs.

The solution to the problem is the evaluation of the feasibility of multiple EEMs in order to prioritise the implementation order thereof.

A methodical way of evaluating multiple EEMs involves decomposing a complex process into a series of smaller and manageable steps. This will also allow the categorisation and labelling of EEMs with similar characteristics in terms of their feasibility status. Furthermore, the structured categorisation and labelling of EEMs will allow the quantification of energy savings and cost savings at each step of the structured approach. This may aid in holistic energy planning.

Flowcharts are utilised throughout this section to illustrate the systematic decision-making process followed throughout the design of the structured approach. A decision-making flowchart is a visual representation of information that depicts the steps followed to reach a decision. The ISO 5807 standard [109] symbols were used for the construction of the flow charts. The ISO common symbols for flowchart construction can be found in Table C-1 of Appendix C.

Since the objective of the study is the prioritisation of multiple EEMs by assessing feasibility criteria, the structured approach is separated into two distinctive phases. **Phase 1** of the structured approach consists of a feasibility assessment of the EEMs. **Phase 2** of the structured approach then prioritises the EEMs that were deemed feasible by the first phase of the approach.

Figure 2-13 illustrates the two phases of the structured approach. The feasibility assessment phase (Phase 1) is indicated in pink, and the prioritisation phase (Phase 2) is indicated in purple. If an EEM does not currently meet the requirements of the relevant feasibility stage, the project is labelled as “On hold” until more information becomes available to adequately assess the EEM.

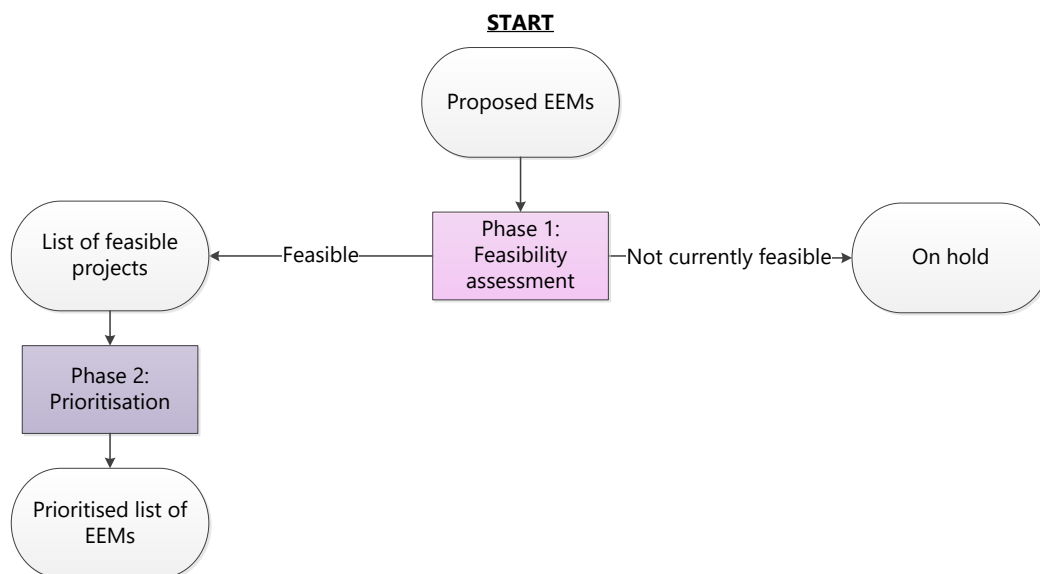


Figure 2-13: High-level structured approach.

Since the prioritisation of EEMs is a complex process that requires multiple conflicting criteria to be weighed against one another, inputs from individuals with energy management experience are required. Therefore, a questionnaire will be utilised to weight the criteria used in the structured approach. The application of the questionnaire results to the structured approach is discussed in Chapter 2, but the questionnaire is only implemented in Chapter 3.

The resulting weighted criteria is used in both Phase 1 and Phase 2 of the structured approach. During Phase 1 of the structured approach, the results from the questionnaire are used to evaluate the complexity of EEMs in order to determine their technical feasibility. The weighted criteria resulting from the questionnaire are also utilised to prioritise the feasible EEMs in Phase 2 of the structured approach. A sample questionnaire is provided in Appendix D. More detail is provided at the relevant sections of each phase of the structured approach.

2.6.1 Phase 1: Feasibility assessment

The first phase of the structured approach consists of a feasibility assessment of multiple EEMs. It is evident from the review of feasibility criteria in Section 2.3 that multiple criteria exist that may influence the feasibility of an EEM. The second requirement of the research objective in Section 1.4 requires the systematic assessment of project feasibility. Therefore, the feasibility assessment is subdivided into three stages as shown in Figure 2-14. Stage 1 is a high-level screening of the proposed EEMs. Stage 2 and Stage 3 evaluate the technical and financial feasibility of the EEMs, respectively.

To ensure a systematic approach to feasibility, a proposed EEM must first pass through one stage of feasibility before progressing to the following stage. The feasibility status of a project may change as more information comes to light or as new technology develops and matures. The feasibility assessment of EEMs may therefore be an iterative process.

The review of feasibility criteria in Section 2.3 illustrated the magnitude of criteria that can be considered during the assessment of project feasibility. The availability of information on certain criteria may not be available for all the EEMs that are to be evaluated [97]. Some financial criteria, such as the Net present value (NPV), require detailed cashflows that may not be available to the assessor of the EEMs. The structured approach was thus designed to consider at least the most critical criteria according to the findings of the literature review presented in Section 2.3.

Table 1-2 showed that the financial feasibility of EEMs is widely considered in literature. In contrast, it was shown that the technical feasibility was not widely considered by the consulted sources from Table 1-2. Therefore, the emphasis of this study is placed on the technical feasibility assessment. A high-level assessment of the financial feasibility is conducted with the evaluation of incentives to potentially improve the business case of the EEMs.

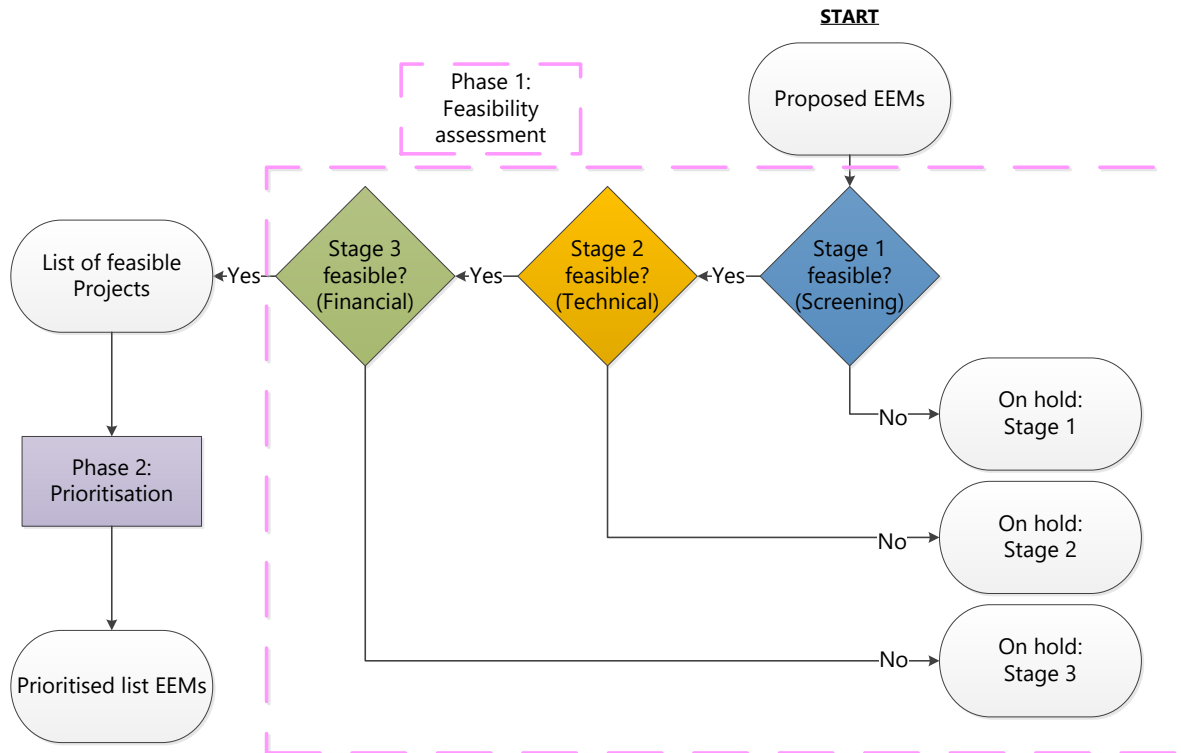


Figure 2-14: The first phase of the structured approach is subdivided into three feasibility stages.

Each stage of the feasibility assessment is discussed in the following sections.

Stage 1: Screening

Organisations have limited human resources to embark on the time-consuming and complex process of determining project feasibility [110]. Thus, the first stage of the feasibility assessment should screen the multitude of available EEMs to ensure that detailed evaluations at the later feasibility stages are reserved for EEMs that are most likely to be feasible overall [110, 111]. The screening criteria consists of an assessment of the availability of technical information as well as some high-level financial feasibility indicators.

Figure 2-15 shows a layout of the first feasibility stage. The specific screening criteria are represented by numbered diamonds (1 to 5), indicating various decisions that need to be made throughout Stage 1 of the feasibility assessment. Each decision is discussed in detail in the following paragraphs.

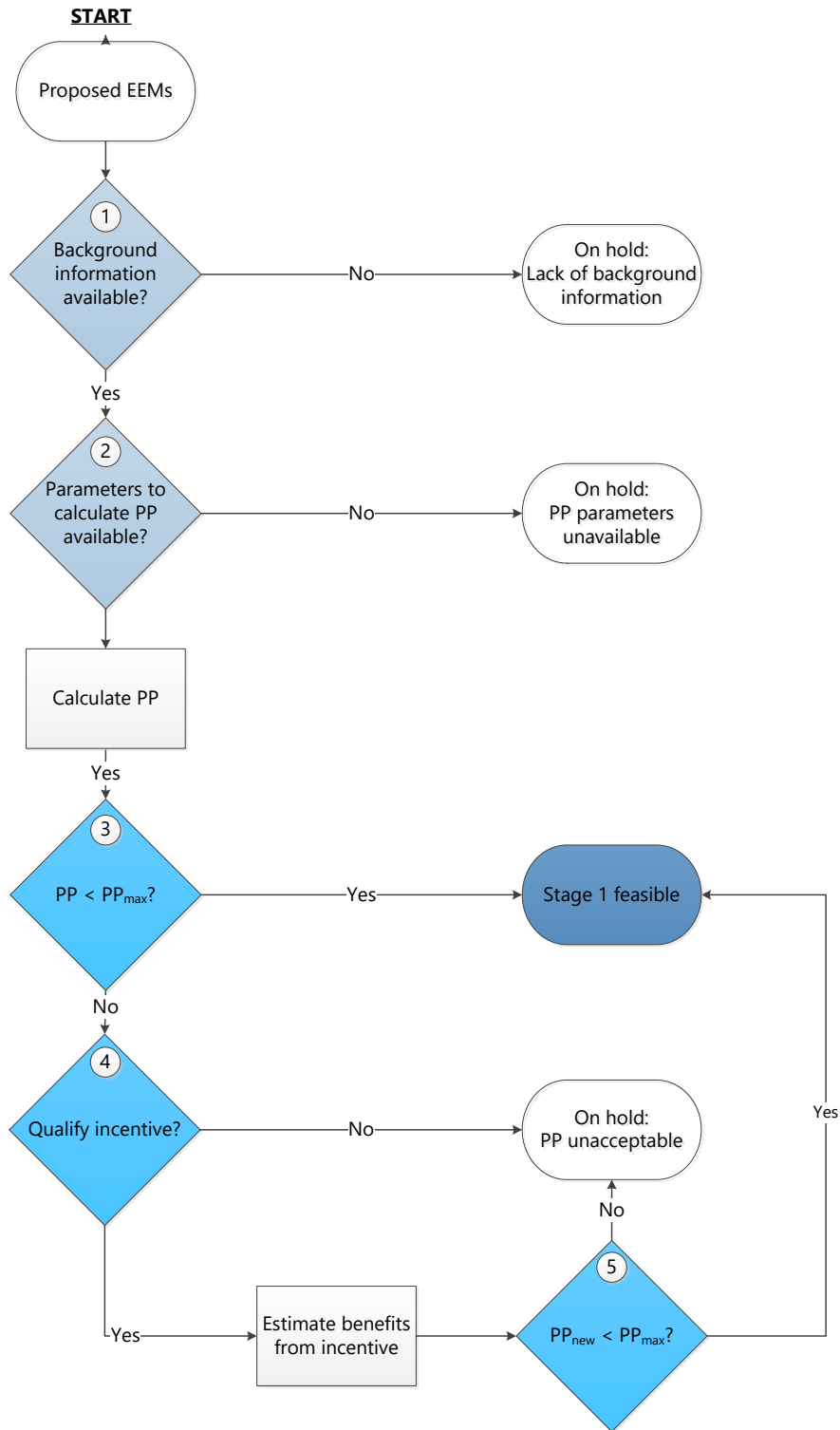


Figure 2-15: Stage 1 of the feasibility assessment of the designed approach.

Although the information on certain criteria for proposed EEMs may be sparse, basic project information is required to evaluate the feasibility of EEMs [111]. A short project description with some background information is crucial to assess the overall feasibility of an EEM since it will be difficult to evaluate specific project criteria without a basic understanding of the proposed measure.

Therefore, as shown by **Decision 1** in Figure 2-15, if a proposed EEM does not contain a description and basic background information, the project should be placed on hold until more information can be obtained.

The PP is a simple method that is commonly used to screen investment projects [112]. The evaluation of projects based on PP also allows for easy comparison between multiple EEMs. Furthermore, most companies have a management policy regarding the maximum allowable PP of a project [97, 112] whereas the limit on the implementation cost may vary based on the availability of capital.

The literature review of financial criteria in Section 2.3.2 showed that *Implementation cost*, *Payback period*, and *Cost savings* were the top three cited criteria. The *Implementation cost* and *Cost savings* are required parameters to calculate the PP with Equation **Error! Reference source not found.**

$$PP = \frac{\textit{Implementation cost}}{\textit{Cost savings}} \quad (9)$$

Therefore, the *Implementation cost* and estimated *Cost savings* should be requested as shown by **Decision 2** in Figure 2-15. These criteria are then used to calculate the PP.

The PPs of the EEMs are evaluated by **Decision 3** in Figure 2-15. If the PP of the EEM under consideration is larger than the maximum allowable PP (PP_{\max}) of the company, a high-level analysis of available incentives should be conducted as illustrated by **Decision 4** in Figure 2-15. This is done to prevent the exclusion of EEMs that may have significant overall benefits if available incentives are utilised. Available incentives for consideration were discussed in Section 2.2 and is summarised in Table 2-1.

If the EEM under consideration qualifies for an incentive, the benefits are estimated. The new PP (PP_{new}) is then calculated, as shown by **Decision 5** in Figure 2-15, to determine whether the incentive can improve the feasibility of the EEM above the required threshold.

Organisations have limited human resources to embark on the time-consuming process of evaluating incentives in detail. Thus, the first stage of the feasibility assessment should merely conduct a high-level estimation of the potential incentive benefits. A high-level estimation of available incentive benefits is conducted to prevent the discarding of EEMs that may be feasible if incentive benefits are included.

Stage 1 of the feasibility assessment is merely a screening of the EEMs, the evaluation of available incentives is limited to estimations of the benefits. Table 2-1 presents a summary of current incentives

with their requirements and expected benefits. Detailed incentive calculations are reserved for Stage 3 of the feasibility assessment.

The implementation of Stage 1 of the feasibility assessment will filter and categorise the proposed EEMs. Figure 2-16 shows an example of the high-level categorisation as a result of applying Stage 1 to a list of proposed EEMs. The percentage of the total initial EEMs allocated to each category are shown by Figure 2-16. This figure is useful to understand why certain EEMs are not considered feasible and to further facilitate the discussion of the results.

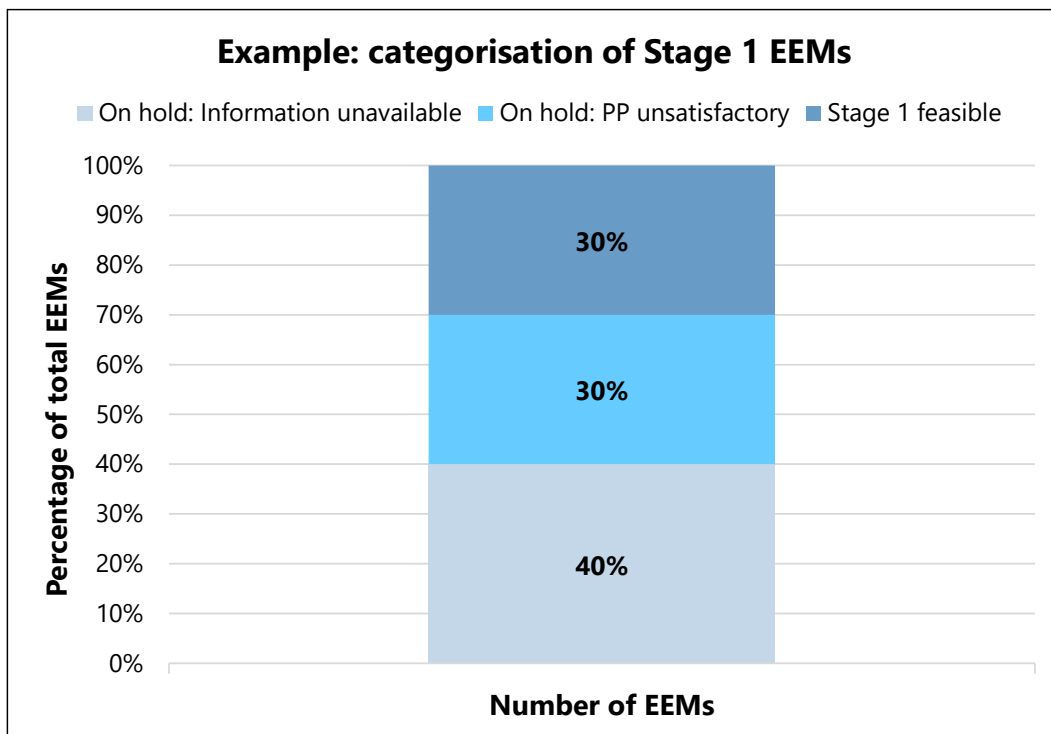


Figure 2-16: Example output of the proposed high-level categorisation of the Stage 1 results.

Stage 1 summary

Stage 1 of the feasibility assessment is a screening stage where the availability of information as well as the high-level performance of the EEMs are assessed. An estimation of available incentive benefits is used to ensure that EEMs with unacceptable PPs are not prematurely placed on hold. The EEMs that are deemed feasible by Stage 1 proceed to Stage 2 of the feasibility assessment.

Stage 2: Technical feasibility

After the initial screening of the proposed EEMs in Stage 1, a more detailed analysis can be conducted to determine the feasibility of the projects. Stage 2 considers the technical specifications of EEMs to determine whether the measures are practical to implement. First, the technical complexity of each

project is determined. Based on the assigned technical complexity level, each EEM is then evaluated for feasibility by considering whether an appropriate method of verification (MOV) is available and has been applied. A high-level layout of the process followed during Stage 2 is shown in Figure 2-17.

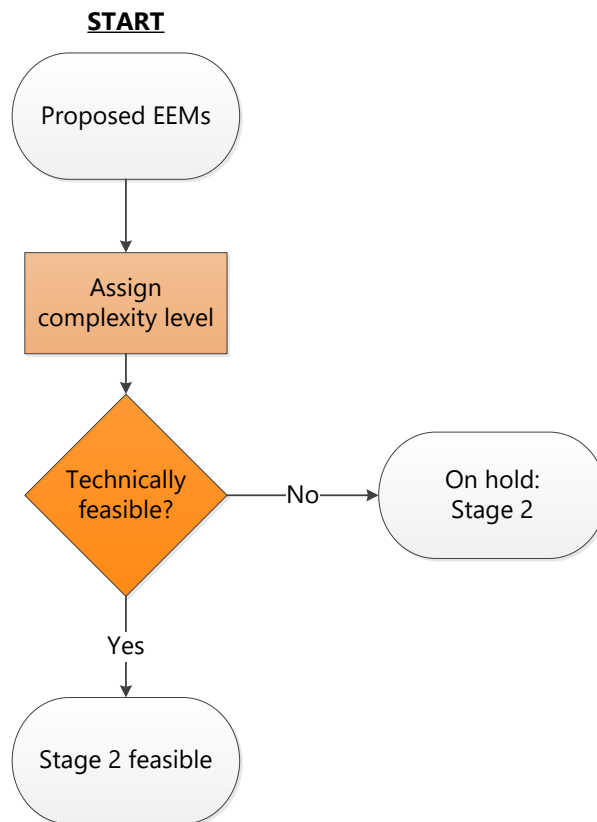


Figure 2-17: High-level layout of Stage 2 of the feasibility assessment.

Complexity level

The technical complexity of EEMs is determined by weighting various complexity criteria before evaluating the complexity of the proposed EEMs. The review of technical feasibility criteria in Section 2.3.1 showed that a wide variety of qualitative and quantitative criteria influence the technical complexity of EEMs.

The *Complexity* criteria were categorised and structured as shown in Figure 2-18 (adapted from Figure 2-3). Since information on all the technical complexity criteria from the review in Section 2.3.1 may not be available, the assessor of the EEMs should review the extensive list of complexity criteria for applicability to the site under consideration.

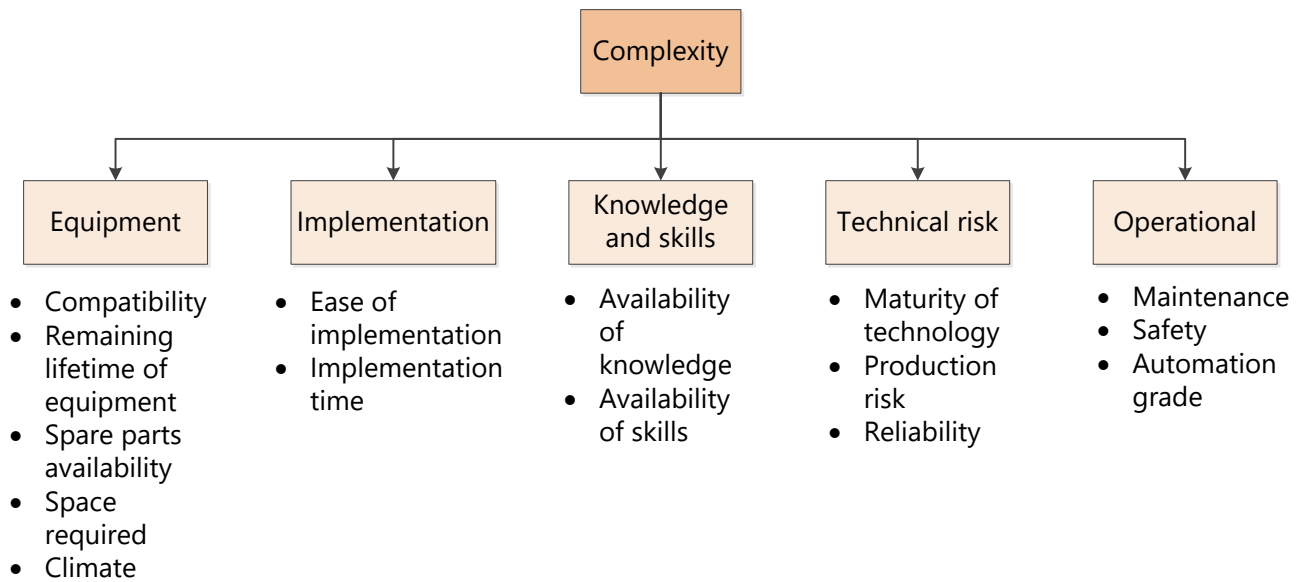


Figure 2-18: The *Complexity* criteria compiled in Section 2.3.1 (adapted from Figure 2-3).

Criteria in MCDM problems are usually not equally weighted and the assignment of weights to the *Complexity* criteria is therefore necessitated. Weights are assigned to the criteria by pair-wise comparisons of each level of the hierarchy according to the AHP procedure outlined in Section 2.5.

As mentioned in Section 2.6, it is recommended that the local weights of the *Complexity* criteria be assigned by individuals with experience in energy management via a questionnaire. The assignment of local weights to the *Complexity* criteria is done in Chapter 3 by completing Table D-5 to Table D-10 of the sample questionnaire in Appendix D.

After the local weights have been assigned to each criterion as well as the parent criteria, the global weight of each criterion is calculated. This is done by multiplying the local weight of each criterion with the weight assigned to its respective parent criterion as outlined in Step 3 of the AHP procedure described in Section 2.5.

An analysis of the global weights is conducted to determine what *Complexity* criteria are considered most important. An example of the global weights of the *Complexity* criteria that may be obtained from the questionnaire are shown in Figure 2-19.

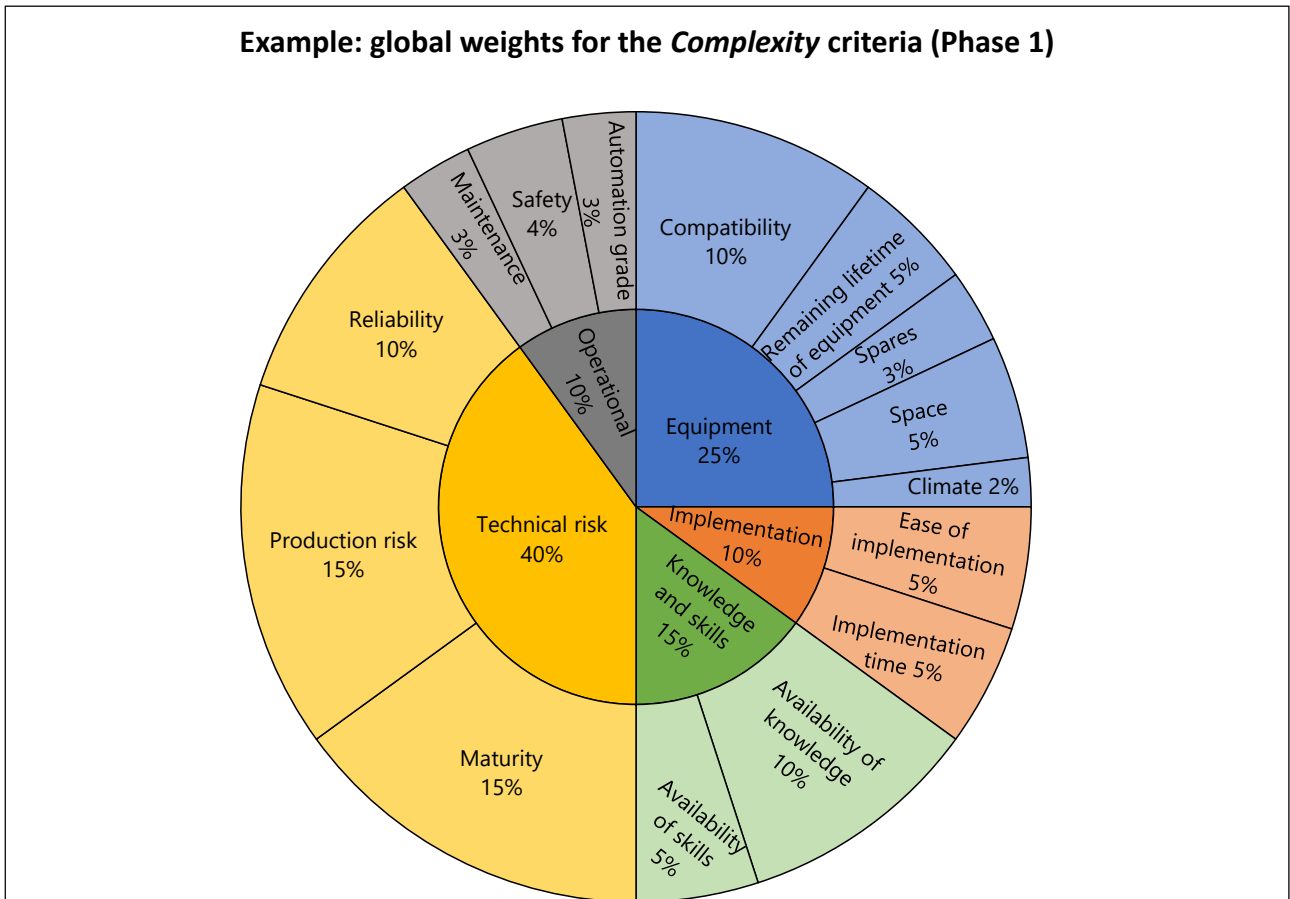


Figure 2-19: Example output of the global weights of the *Complexity* criteria for Phase 1.

The global weights can be compared to the findings of the literature review of feasibility criteria in Section 2.3 to determine if the questionnaire results of Chapter 3 are validated by the literature.

To determine the complexity score of each EEM, complexity ratings models are needed to compare the qualitative complexity criteria of the EEMs. A ratings model was developed for each qualitative criterion with the assignment of a rating between 1 and 3. The ratings were developed by the author by considering various situations that may occur with respect to each criterion. Since the higher rating should reflect the greater convenience with regards to the alternatives, a value of 3 indicates low complexity and a value of 1 indicates high complexity with regards to the criterion. Table 2-9 shows the developed ratings model for the qualitative criteria.

Table 2-9: A ratings model for the evaluation of qualitative *Complexity* criteria.

Criterion	Rating 1 definition	Rating 2 definition	Rating 3 definition
<i>Compatibility</i>	New infrastructure required or significant adaption of current infrastructure.	Notable adjustments to current infrastructure.	Minor adjustments to current infrastructure.
<i>Spare parts availability</i>	Few suppliers available that are not locally situated.	Not many local suppliers available.	Abundance of local suppliers available.
<i>Space required</i>	Acquisition of additional space required.	Additional space required is available.	No additional space required.
<i>Climate</i>	Performance of the technology is severely impacted by the climate – the climate is not agreeable with the technology.	Performance of technology has some dependence on the climate that is manageable.	Performance of technology is not dependent on the climate.
<i>Ease of implementation</i>	Difficult implementation with a shutdown required and/or dependence on other projects.	Easy implementation with a short shutdown of production required.	Easy implementation with no shutdown of production required.
<i>Availability of knowledge</i>	Few experts available that are located far away.	Expertise available locally.	Existing personnel with the required knowledge.
<i>Availability of skills</i>	New skilled personnel required, or comprehensive training required for existing personnel.	Existing personnel but additional training required.	Existing personnel with the required skills.
<i>Maturity of technology</i>	New technology.	Mature technology that is not so widely used or mature technology incorporating new features.	Mature technology that is widely used in the industry.
<i>Production risk</i>	High production risk.	Medium production risk.	Low or no production risk.

Criterion	Rating 1 definition	Rating 2 definition	Rating 3 definition
<i>Reliability</i>	Technology with a high rate of failure and/or performance not close to the designed output.	Technology with a medium rate of failure and/or performance similar to the designed output.	Technology with a low rate of failure and/or actual performance close to the designed output.
<i>Maintenance</i>	Significant increased frequency/difficulty of maintenance.	Some additional maintenance required.	No additional maintenance or reduced maintenance of the system required.
<i>Safety</i>	Highly specialised safety procedures required.	Additional safety procedures and training required.	Existing safety procedures are adequate.
<i>Automation grade</i>	Manual process with extensive human input required.	Automated process with human inputs required.	Fully automated with little human supervision required.

The local weight of each EEM with respect to each qualitative criterion in Table 2-9 is calculated by normalisation as described in Step 3 of Section 2.5. For the quantitative complexity criteria, the numerical value of the EEM with respect to the criterion is chosen as its rating. After the assignment of local weights to each of the EEMs, the final complexity score of each EEM is calculated using Equation (8) in Section 2.5.

The EEMs are classified according to their complexity level based on their final complexity score. Due to normalisation, the final complexity scores of all the EEM sum to one. One of three complexity levels, namely *High*, *Medium*, or *Low*, is assigned to each EEM. The parameters of each complexity level are determined by calculating the range between the highest (C_{max}) and lowest (C_{min}) normalised complexity score and dividing the range by three to obtain the interval (i). The complexity level is thus assigned to each EEM according to Table 2-10.

Table 2-10: The complexity level of the EEMs is assigned based on the final complexity score.

Complexity score	Complexity level
Between C_{min} and $C_{min} + i$	High
Between $C_{min} + i$ and $C_{min} + 2i$	Medium
Between $C_{min} + 2i$ and C_{max}	Low

Consider an example to illustrate the process. Five EEMs, labelled A to E, have final complexity scores between 0.1 (C_{min}) and 0.3 (C_{max}). The final complexity scores of the five EEMs sum to one. The range between the lowest and highest complexity scores is calculated as 0.2. Based on the three possible

complexity levels, the interval (i) between each level is calculated as $0.2/3 \approx 0.067$. The complexity levels of the EEMs A to E are thus assigned according to Table 2-11.

Table 2-11: An example of the assignment of complexity levels to EEMs.

EEM	Complexity score	Complexity level
A	0.3	Low
B	0.25	Low
C	0.2	Low
D	0.15	Medium
E	0.1	High

The EEMs are categorised based on complexity level as shown by the colour key in Figure 2-20.

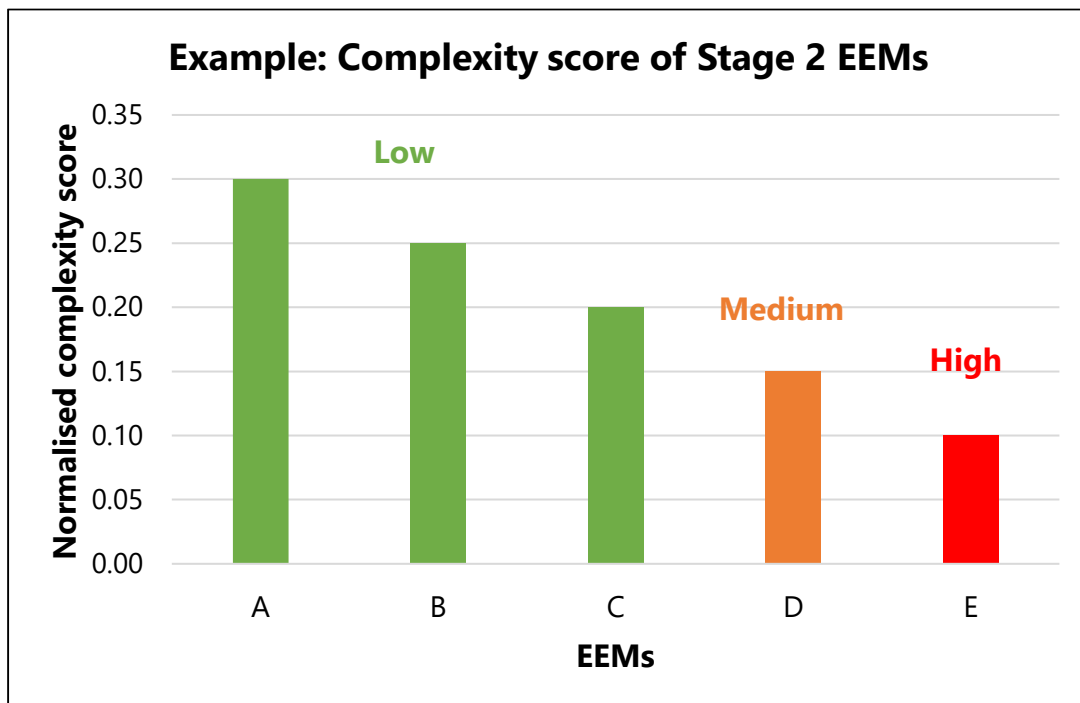


Figure 2-20: Example output of the complexity scores assigned to the list of EEMs.

While project complexity may be helpful to identify projects that can be easily implemented, EEMs with high technical complexities should not be discounted outright. This is because complex EEMs may have substantial benefits that justify the project complexity.

Technical feasibility

After establishing the complexity of the EEMs, the high-level layout of Stage 2 shown in Figure 2-17 is systematically deconstructed to evaluate the technical feasibility, as shown in Figure 2-21. The technical feasibility evaluation is represented by numbered diamonds (1 to 3) in Figure 2-21,

indicating various decisions that need to be made. Each decision is discussed in detail in the following paragraphs.

The technical feasibility is first assessed by determining whether a satisfactory MOV exists for each of the EEMs, as shown by **Decision 1** in Figure 2-21. Complex EEMs may have substantial benefits and should therefore not be excluded outright based on complexity alone. However, the technical complexity of a project may lead to uncertainty regarding its practicality for implementation [113].

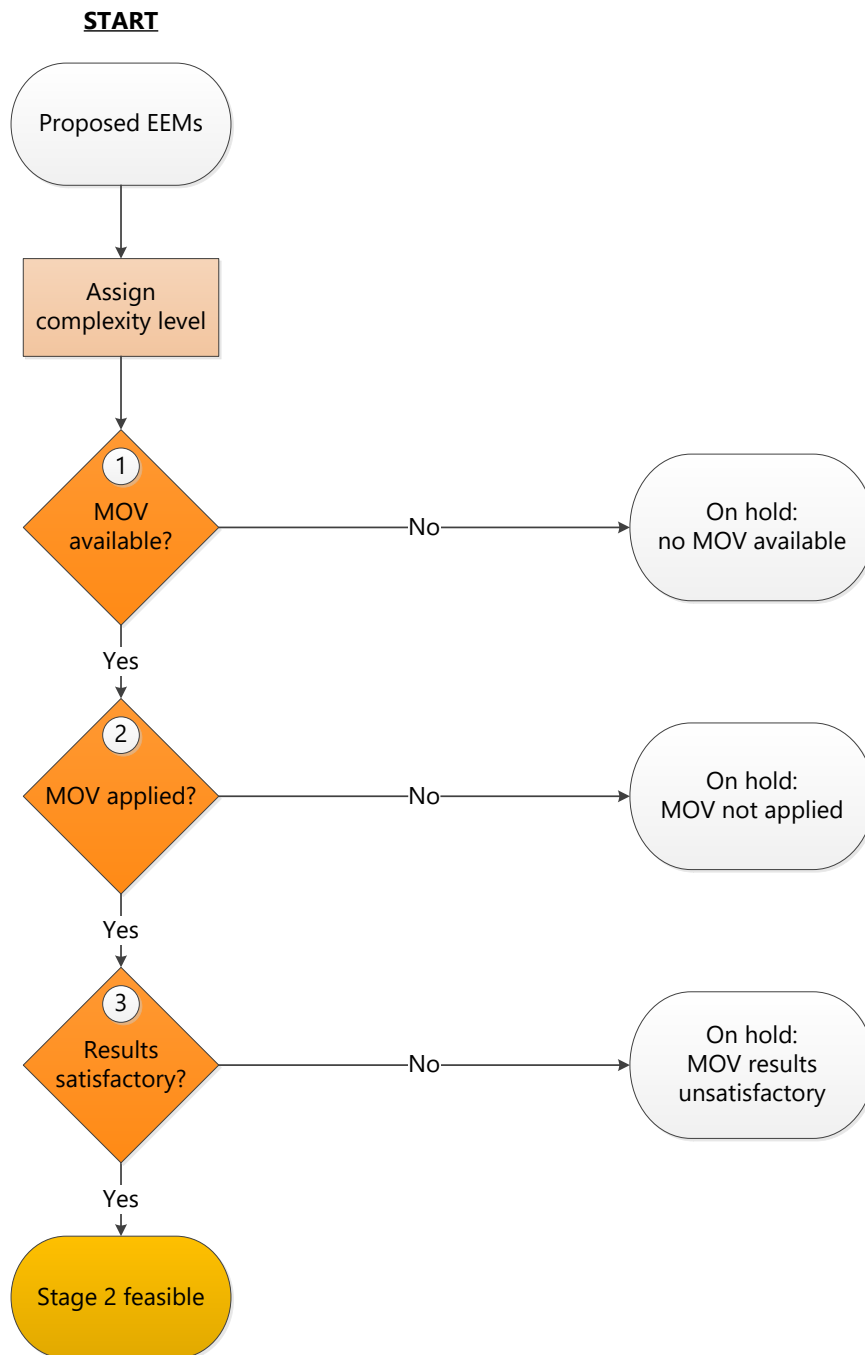


Figure 2-21: Stage 2 of the feasibility assessment of the designed approach.

There is a variety of verification methods available to manage the technical uncertainty associated with complex projects:

- Conducting trial runs or iterative tests to determine the likelihood of project success [114]
- Simulation of the EEM and the interactive effects on the system. Multiple solutions and the effects thereof can be simulated without any physical changes to the system, thereby minimising risk [115]
- Detailed modelling and/or calculations
- Detailed literature review and further research on the proposed EEM
- Performance guarantees from suppliers/Energy services companies (ESCOs) [88, 116]
- Proof of performance from similar previously implemented projects [111]

The project complexity level will ultimately determine the extent of the verification required. For example, a high complexity project may require simulations whereas a lower complexity project can be satisfactorily verified with proof of performance and/or supplier guarantees. Examples of the minimum requirements of the verification method for each complexity level were developed by the author and are given in Table 2-12.

Table 2-12: The minimum MOV required based on the complexity of the EEM.

Complexity level	Minimum MOV
High	Trial run or simulation and one other MOV
Medium	At least two of any of the MOV
Low	At least one of any of the MOV

Decision 1 in Figure 2-21 shows that if there is no satisfactory MOV available, the EEM is placed on hold until a suitable verification method for the EEM is identified.

The next step is to determine whether the MOV has been applied, as shown by **Decision 2** in Figure 2-21. If the MOV has not yet been applied to the EEM, the technical feasibility of the EEM cannot be judged and the project is placed on hold until the outcome of applying the MOV is obtained.

If the MOV has been applied, the outcome of the verification method is evaluated by **Decision 3** in Figure 2-21 to determine whether the EEM is technically feasible.

The implementation of Stage 2 of the feasibility assessment will filter and categorise the proposed EEMs. An example of the high-level categorisation as a result of applying Stage 2 to a list of proposed

EEMs is illustrated by Figure 2-22. The percentage of the total initial EEMs allocated to each category is shown by Figure 2-22 to further facilitate the discussion of the results. The deconstruction provided in Figure 2-22 aims to provide the reasons why certain EEMs will not be considered technically feasible when this method is applied.

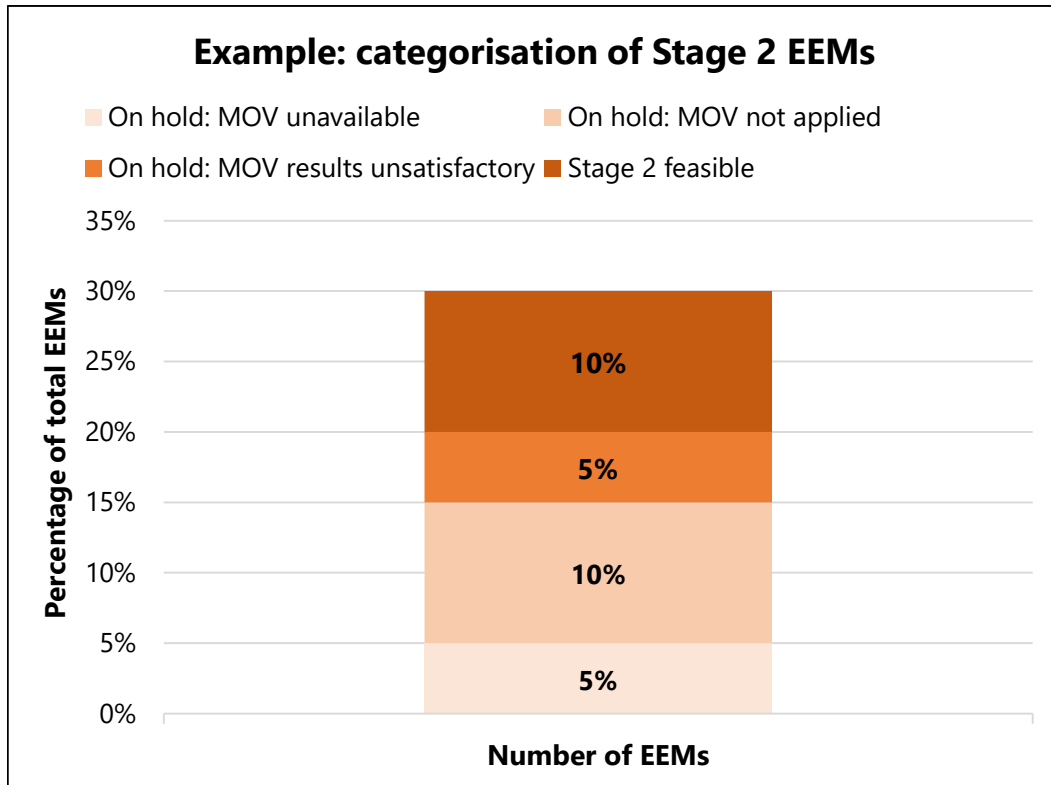


Figure 2-22: Example output of the high-level categorisation of the Stage 2 results.

The measures that are deemed feasible by Stage 2 may progress to Stage 3 of the feasibility assessment.

Stage 2 summary

Stage 2 of the feasibility assessment assesses the complexity level of the EEMs before the technical feasibility thereof is evaluated. The complexity level for each EEM is determined using weighted complexity criteria and ratings assigned to each EEM relative to each complexity criteria. Based on the complexity level, the EEMs are evaluated for technical feasibility: a suitable MOV should be identified, applied, and the results of the application should be satisfactory before an EEM is deemed feasible by Stage 2. The EEMs deemed feasibly in Stage 2 can progress to Stage 3 of the approach.

Stage 3: Financial feasibility

The final stage of the feasibility assessment involves a financial analysis of the EEMs. The research objective stated in Section 1.4 requires the evaluation of financial incentives as part of the structured approach. Therefore, Stage 3 of the feasibility assessment involves the assessment of qualifying incentives as well as the financial analysis of the EEMs. A high-level layout of Stage 3 is shown in Figure 2-23.

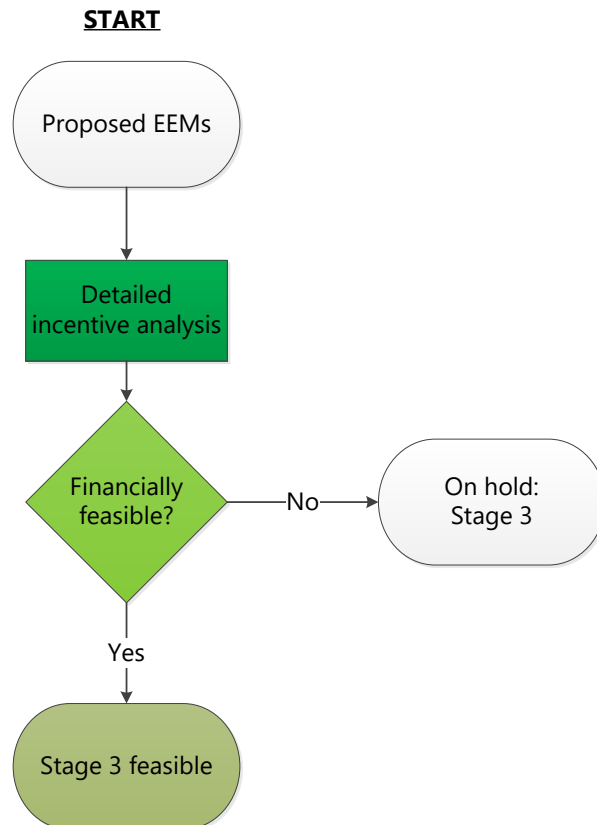


Figure 2-23: High-level layout of Stage 3 of the feasibility assessment.

Since detailed financial metrics such as cashflows may not be available to the assessor of EEMs, the financial feasibility assessment of the study is limited to a high-level assessment. However, if additional financial information, such as the NPV, is available for the proposed EEMs, the financial feasibility assessment of Stage 3 may be extended to include additional criteria.

The PP is a simple method that is commonly used to screen investment projects [112, 117, 118]. The evaluation of projects based on PP also allows for easy comparison between multiple EEMs. Furthermore, most companies have a management policy regarding the maximum allowable PP of a project [97, 112, 118]. Thus, the PP is an easily comparable metric for high-level financial feasibility assessments [112, 117, 118].

The high-level layout of Stage 3 shown in Figure 2-23 is systematically deconstructed in Figure 2-24 to evaluate the financial incentives as part of the feasibility assessment. The decision process is represented by numbered diamonds (1 to 4) and each decision is discussed in detail in the following paragraphs.

An analysis of available incentives was conducted during Stage 1 to determine if the business case of EEMs with unacceptable PPs may be improved. The evaluation of incentives during Stage 1 was limited to rough estimations and detailed calculations of the qualifying incentives are reserved for Stage 3 of the feasibility assessment.

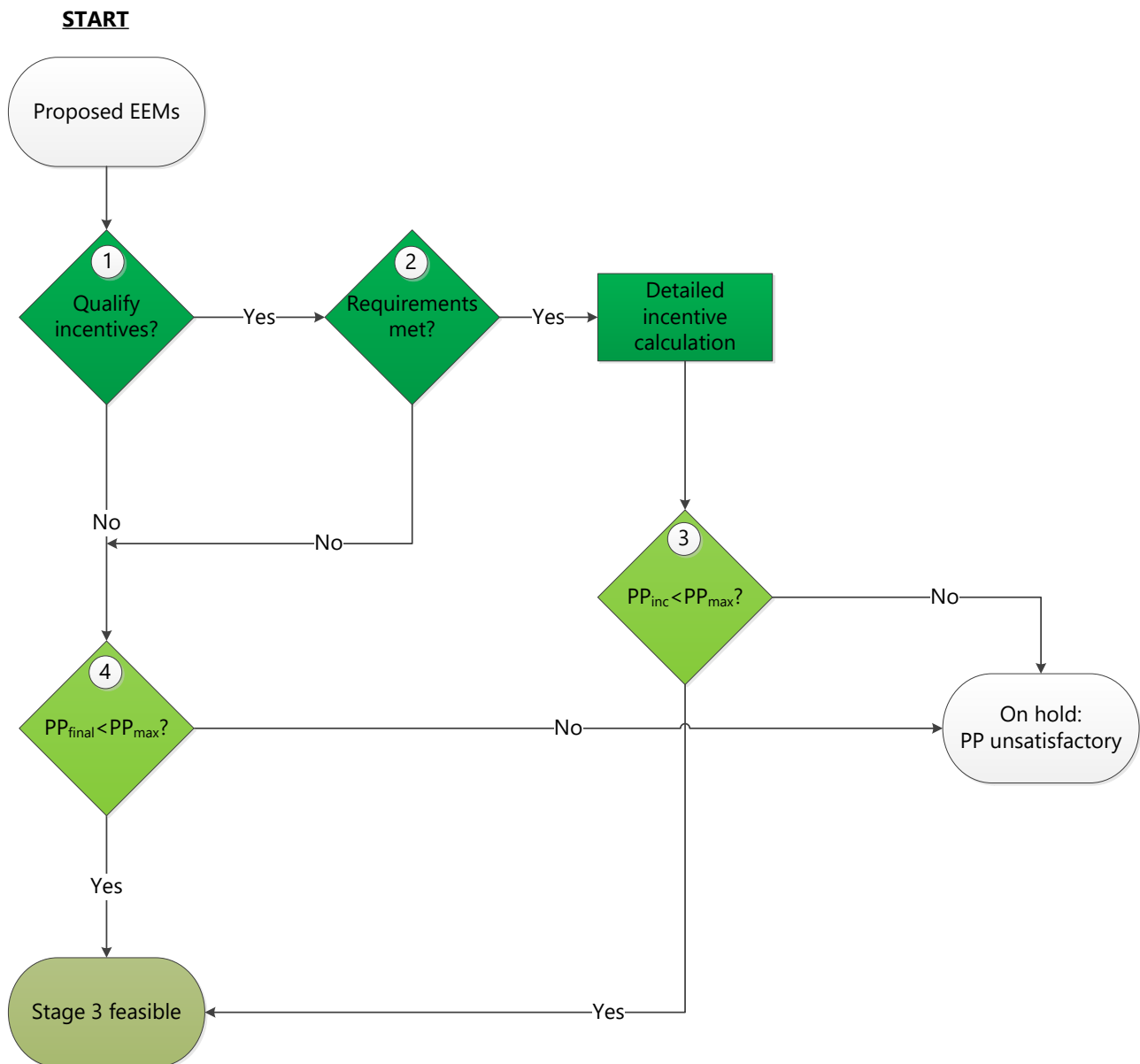


Figure 2-24: The complete process for Stage 3 of the feasibility assessment.

The eligibility of the remaining EEMs is evaluated for any incentives as shown by **Decision 1** in Figure 2-24. If an EEM does not qualify for an incentive, the financial feasibility of the EEM is assessed next. However, if the EEM qualifies for an incentive, it is evaluated whether the EEM meets all the requirements of the incentive to enable a successful outcome, as shown by **Decision 2**. As discussed in Section 2.2, the detailed discussion of available incentives and their requirements are beyond the scope of this study.

If the EEM does not meet the requirements of the incentive that it qualifies for, the financial feasibility of the EEM is assessed next. However, if there is a high level of certainty that the EEM meets the requirements of the incentive, detailed calculations are done to determine the expected benefits from the incentive.

Once the incentive evaluation is completed, the financial feasibility of the EEMs is assessed. The review of financial feasibility criteria in Section 2.3.2 showed that a wide variety of criteria may be utilised to evaluate the financial feasibility of EEMs. However, some of the financial criteria, such as the NPV, may require detailed cashflows that may not easily be available to the assessor of the EEMs [97]. Therefore, the financial analysis of the EEMs in this designed approach is limited to a high-level assessment of the PP.

The PP is chosen as the evaluation criterion since it allows easy comparison of different EEMs and most companies have a management policy regarding the maximum allowable PP of a project [97, 112, 118]. If additional financial information is available for the proposed EEMs, the financial feasibility assessment of Stage 3 may be extended to include additional parameters, such as the NPV. If the EEM qualifies for an incentive and meets all the requirements, the final PP is calculated with the incentive benefit included and evaluated as shown by **Decision 3** in Figure 2-24. If the EEM does not qualify for an incentive, the PP from Stage 1 of the feasibility assessment may be used, and the final PP is evaluated as shown by **Decision 4** in Figure 2-24.

If the final PP of an EEM is less than the maximum allowable PP (PP_{max}), the EEM is considered financially feasible. If the final PP of an EEM is more than PP_{max} , the EEM is placed on hold. The calculation of the PP for EEMs qualifying for incentives are shown separately in Figure 2-24 to clearly distinguish the EEMs that are not feasible despite the added benefits of the incentive.

The implementation of Stage 3 of the feasibility assessment will filter and categorise the proposed EEMs based on their financial feasibility status. The high-level categorisation as a result of applying

Stage 3 to the list of proposed EEMs is illustrated by Figure 2-25. The percentage of the total initial EEMs allocated to each category are shown by Figure 2-25 to further facilitate the discussion of the results.

Figure 2-25 distinguishes between EEMs that are Stage 3 feasible by considering whether there are qualifying incentives for the EEMs. Some EEMs may not qualify for any incentives but are nonetheless financially feasible. Other EEMs may qualify for incentives but are deemed financially feasible without taking the incentive benefits into account. Some EEMs may only be feasible as a result of the added benefits from the qualifying incentives.

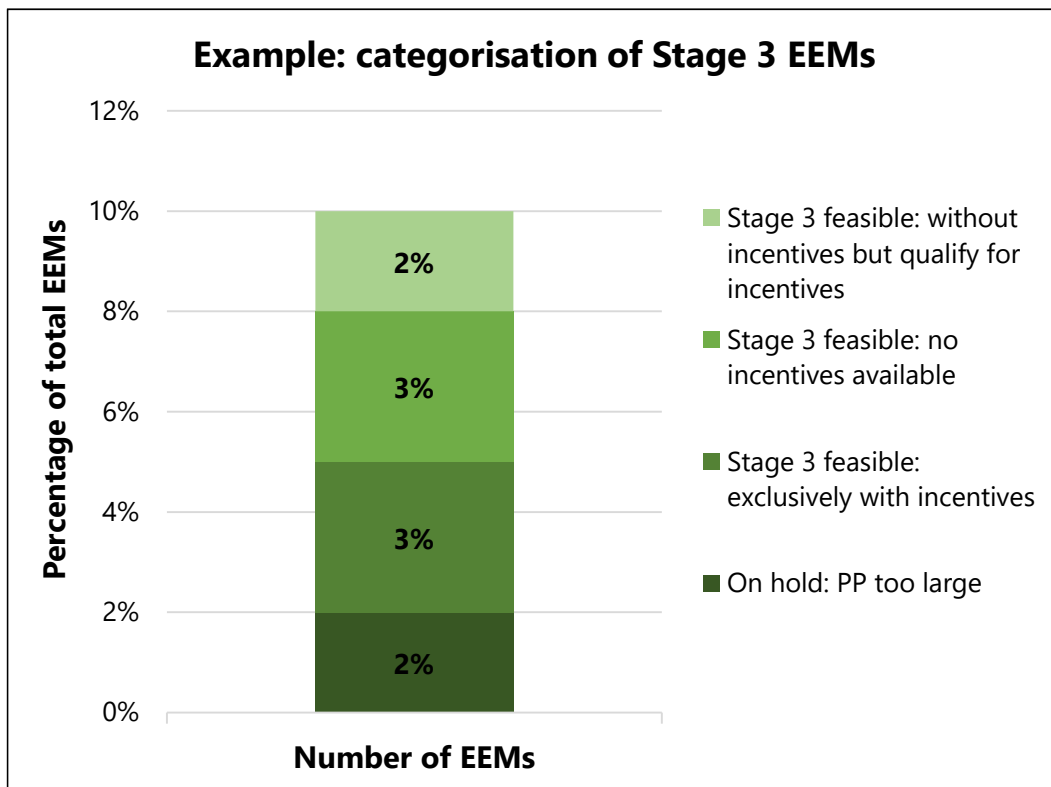


Figure 2-25: Example output of the proposed high-level categorisation of the Stage 3 results.

The EEMs that are deemed feasible by Stage 3 are added to the final list of feasible EEMs.

Phase 1 conclusion

Phase 1 of the designed approach consists of three stages of feasibility assessment. The high-level steps of each stage of Phase 1 are summarised by Figure 2-26.

Stage 1 of the feasibility assessment is a screening stage where the availability of information and high-level performance indicators are evaluated. Stage 2 determines the complexity level of the remaining EEMs, and the technical feasibility of the EEMs is evaluated based on the MOV available.

Stage 3 of the feasibility assessment evaluates the financial feasibility of the EEMs by considering the PP and available incentives.

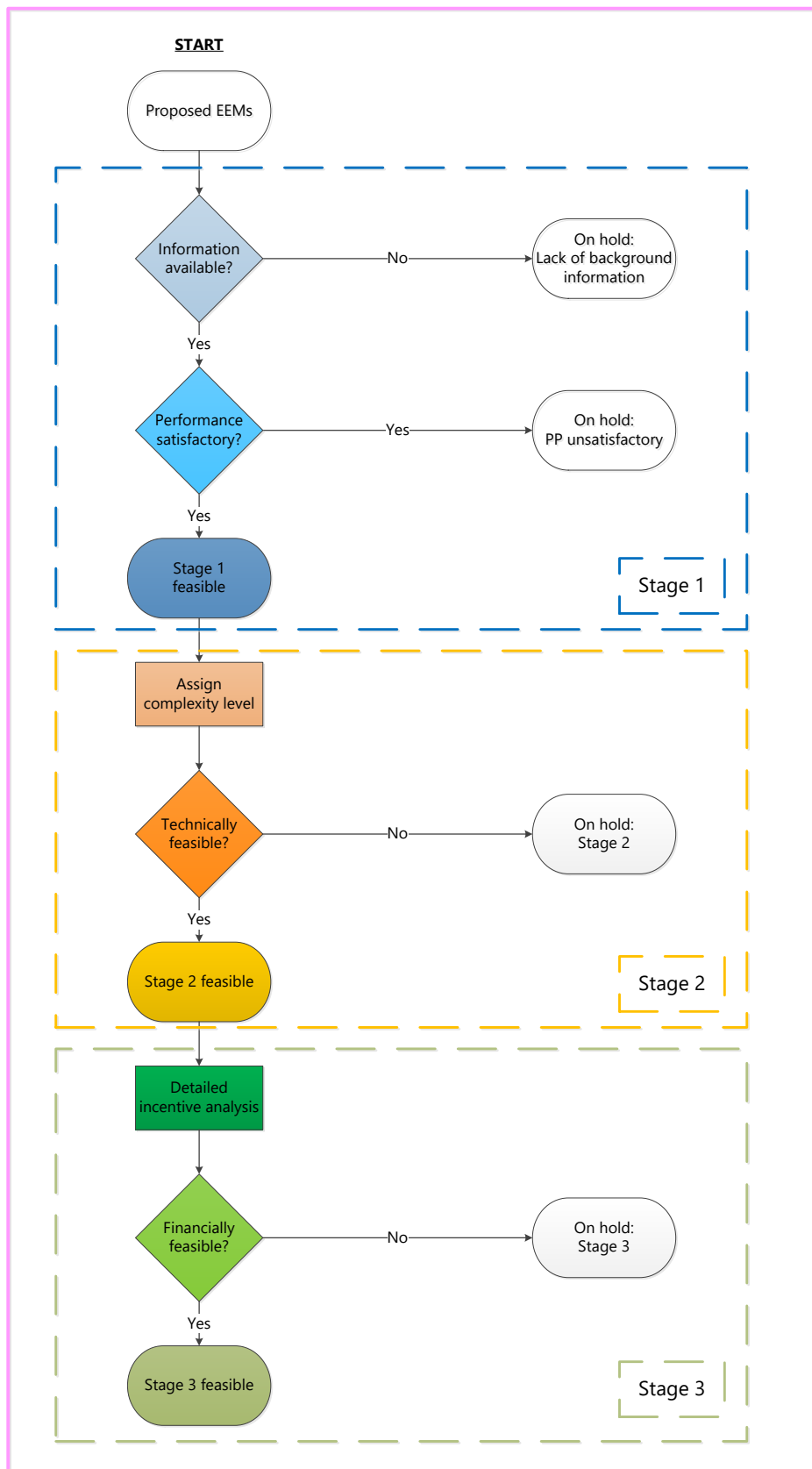


Figure 2-26: A summary of Phase 1 with the three stages of feasibility assessment.

The results of applying Phase 1 can be summarised as shown by the example in Figure 2-27. Figure 2-27 distinguishes between the EEMs that are feasible and those that are placed on hold. The percentage of EEMs that are placed on hold during each stage of the feasibility assessment is shown separately on Figure 2-27.

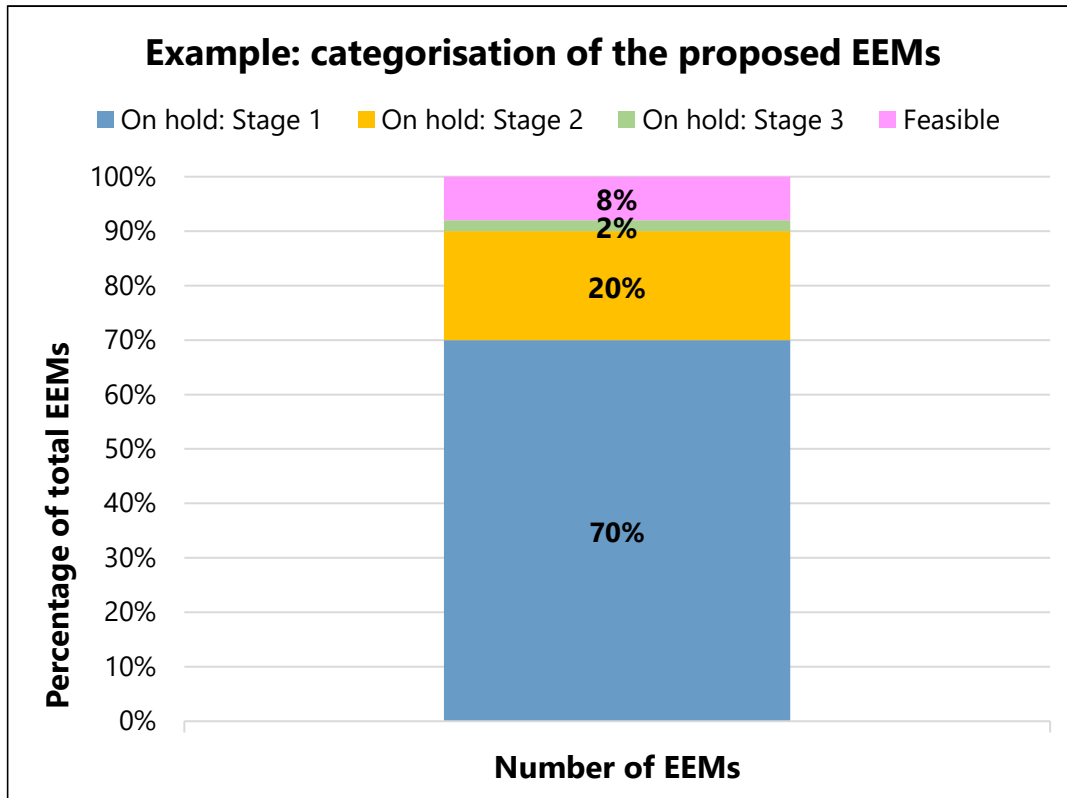


Figure 2-27: Example output of the proposed high-level categorisation of the Phase 1 results.

The EEMs that are deemed feasible by Phase 1 of the structured approach proceed to Phase 2 where the EEMs are prioritised.

2.6.2 Phase 2: Prioritisation

The EEMs that were deemed feasible by Phase 1 of the structured approach are prioritised by Phase 2 as shown by the purple shading in Figure 2-28. The selection of prioritisation criteria and their subsequent weighting are discussed in the subsections that follow.

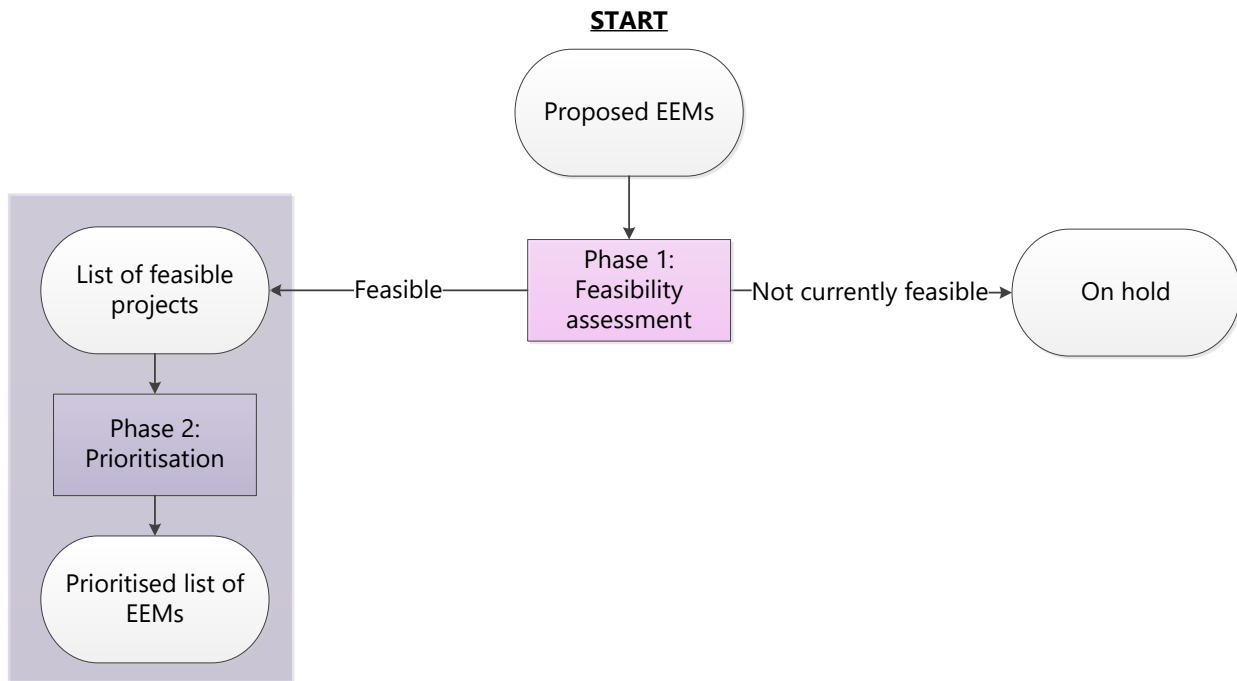


Figure 2-28: High-level structured approach (repeat of Figure 2-13).

Selection of prioritisation criteria

Various technical and financial criteria were reviewed in Section 2.3. The criteria were structured into hierarchies, as shown in Figure 2-3 and Figure 2-5. As discussed in Section 2.4, the feasibility criteria identified in Section 2.3 are used as the prioritisation criteria. Therefore, the combined hierarchy for the prioritisation criteria is shown in Figure 2-29. The hierarchy in Figure 2-29 is used for the weighting of the criteria according to the AHP process described in Section 2.5.

Since information on all the prioritisation criteria may not be available, the assessor of the EEMs may select prioritisation criteria relevant to the company. However, it is recommended that at least the feasibility criteria selected in Phase 1 of the designed approach are used as the prioritisation criteria during Phase 2.

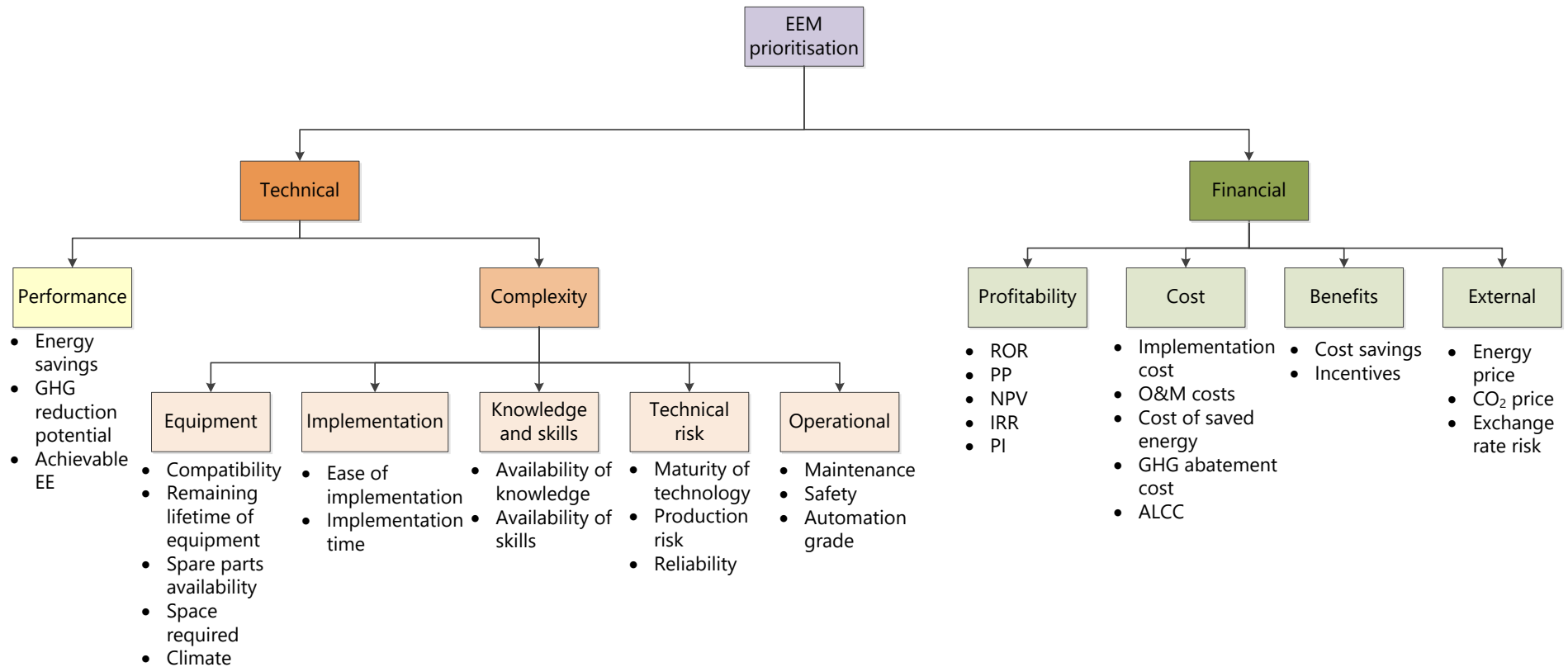


Figure 2-29: The hierarchy of the prioritisation criteria.

Weighting of the prioritisation criteria

It is recommended that the weights of the prioritisation criteria be assigned by individuals with experience in energy management via a questionnaire (facilitated in Chapter 3). A sample questionnaire for the assignment of weights to the prioritisation criteria is available in Appendix D.

The questionnaire responses are aggregated by the *aggregation of individual judgements* (AIJ) procedure [119]. During the AIJ procedure, the individual judgmental matrices are aggregated to form new judgement matrices for the group [120]. This is done by calculating the weighted geometric mean of all K participants' individual judgements (pw_{Ck}) to form the consolidated decision matrix. First, the sum over K participants (pw_{Cx}) is found as shown by Equation (10)

$$pw_{Cx} = \sum_{k=1}^K \ln(pw_{Ck}) \tag{10}$$

The geometric mean (pw_{Ccons}) is then calculated by Equation (11)

$$pw_{Ccons} = e^{\frac{pw_{Cx}}{K}} \tag{11}$$

The global weights are calculated from the aggregated judgmental matrices according to the AHP procedure described in Section 2.5. An analysis of the global weights is conducted to determine what criteria are considered most important by the questionnaire respondents. The global weights are compared to the findings of the literature review of feasibility criteria in Section 2.3 to determine if the questionnaire results in Chapter 3 are validated by the literature.

Figure 2-30 shows an example of how the global weights of the high-level criteria can be presented. From Figure 2-30 the importance of the *Technical* category can be compared to that of the *Financial* category. Furthermore, the global weights of the criteria comprising each category can be compared to one another, as well as to the findings from the literature reviews in Section 2.3.

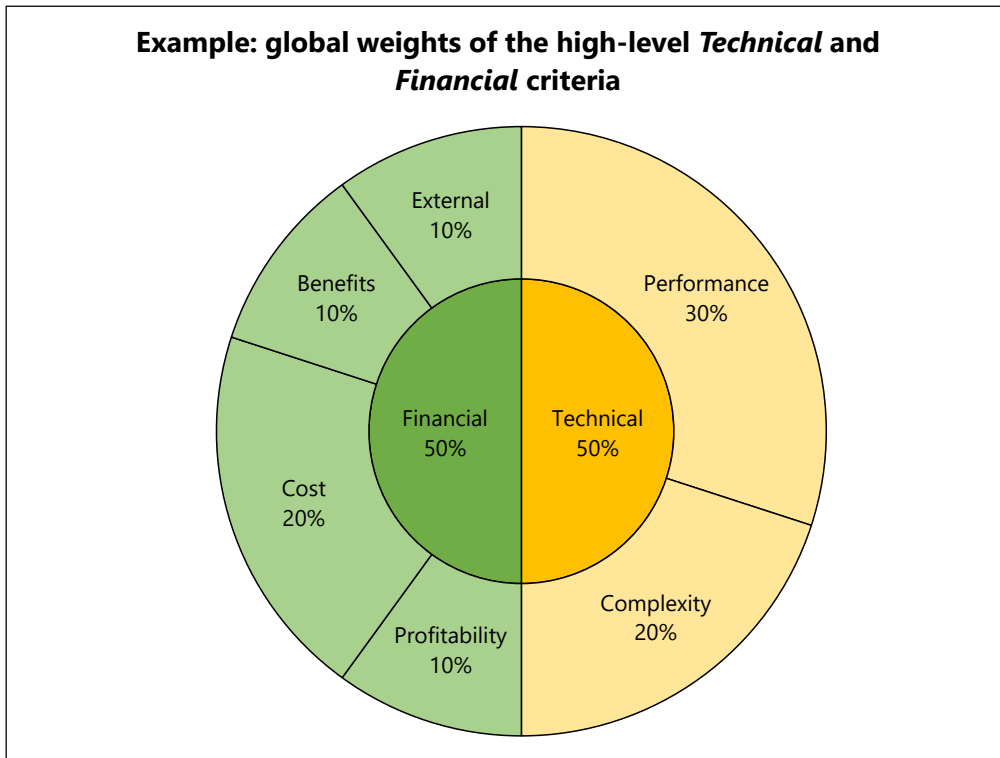


Figure 2-30: Example output of the global weights of the high-level criteria.

The discussion of the global weights can be elaborated by comparing the criteria comprising the *Technical* and the *Financial* criteria groups, as shown by Figure 2-31 and Figure 2-32.

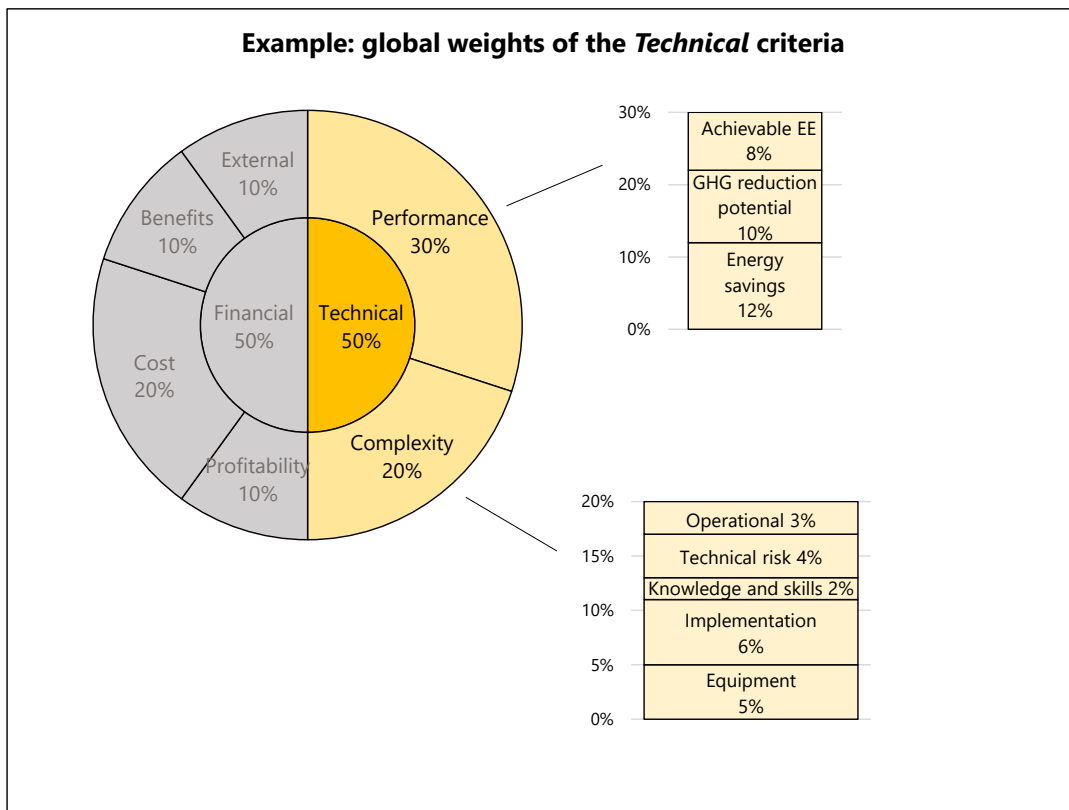


Figure 2-31: Example output of the global weights of the *Technical* criteria.

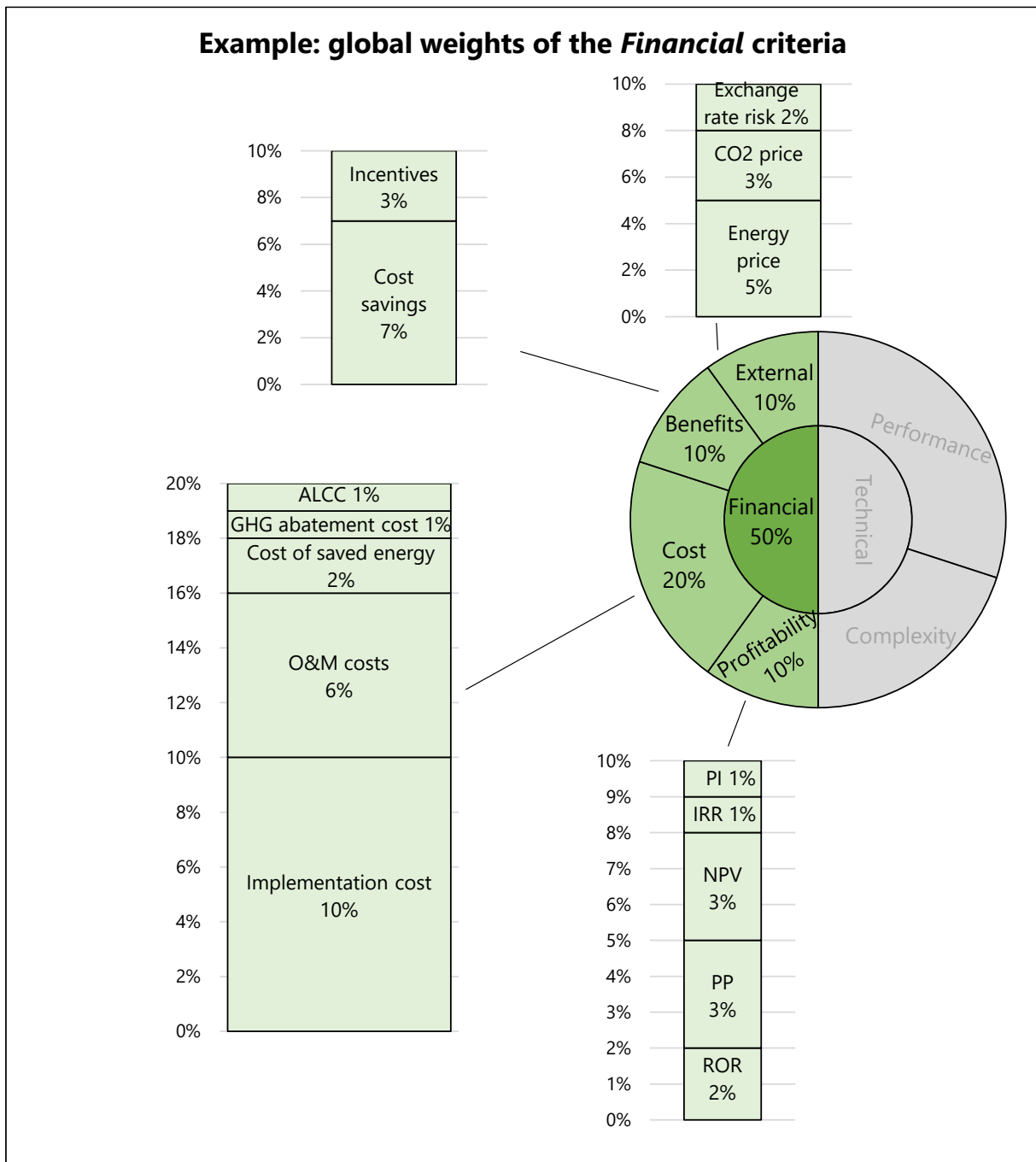


Figure 2-32: Example output of the global weights of the *Financial* criteria.

The global weights of the *Technical* criteria group can be further isolated by considering the global weights of the *Complexity* criteria as shown in Figure 2-33. The global weights of the *Complexity* criteria in Figure 2-33 differ from the global weights of the *Complexity* criteria in Figure 2-19. This is because the complete prioritisation hierarchy of Figure 2-29 is weighted in Phase 2 where only the *Complexity* hierarchy was weighted in Stage 2 of Phase 1 (Section 2.6.1). Since the global weights of each complete hierarchy sum to one, the global weights of the *Complexity* criteria in Stage 2 of Phase 1 (Section 2.6.1) differ from the global weights assigned to the *Complexity* criteria in Phase 2.

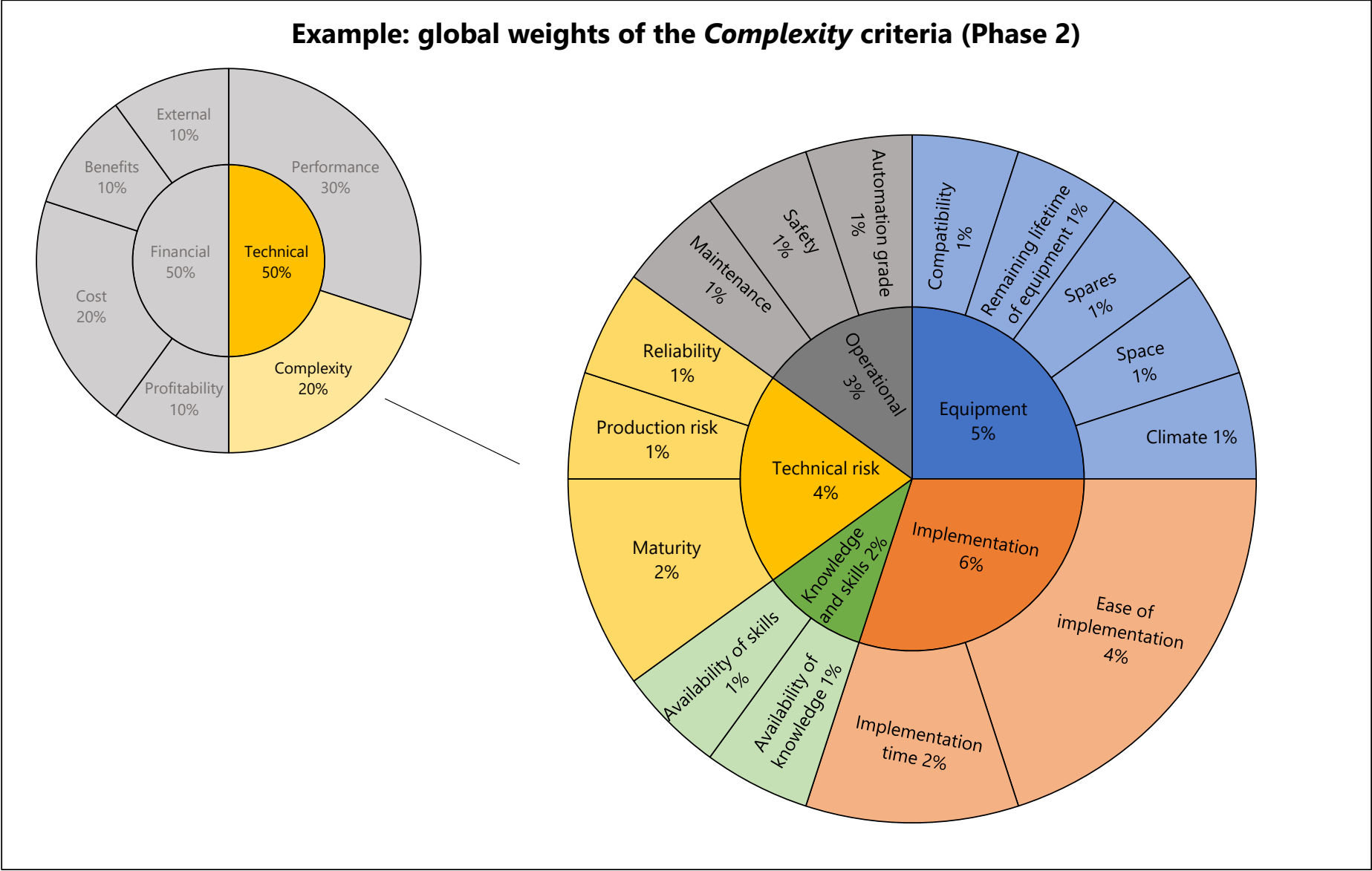


Figure 2-33: Example output of the global weights of the *Complexity* criteria for Phase 2.

Figure 2-34 shows that the global weights of the criteria on the lowest levels of the prioritisation hierarchy are compared to one another to gain an understanding of the individual criterion contribution to the project prioritisation. The most important criteria are compared to the least important criteria and the questionnaire findings of Chapter 3 will be compared to those of the literature review in Section 2.3.

After the global weights of the prioritisation criteria are calculated from the questionnaire results (conducted in Chapter 3), the EEMs that proceeded to Phase 2 of the structured approach are evaluated. A rating is assigned to each EEM with respect to each criterion. If the criterion is qualitative, the ratings scales developed in Table 2-9 are used. For the quantitative criteria, the numerical value of the EEM with respect to the criterion is chosen as its rating. The local weight of each EEM with respect to each criterion is calculated by normalisation as described in Step 3 of Section 2.5.

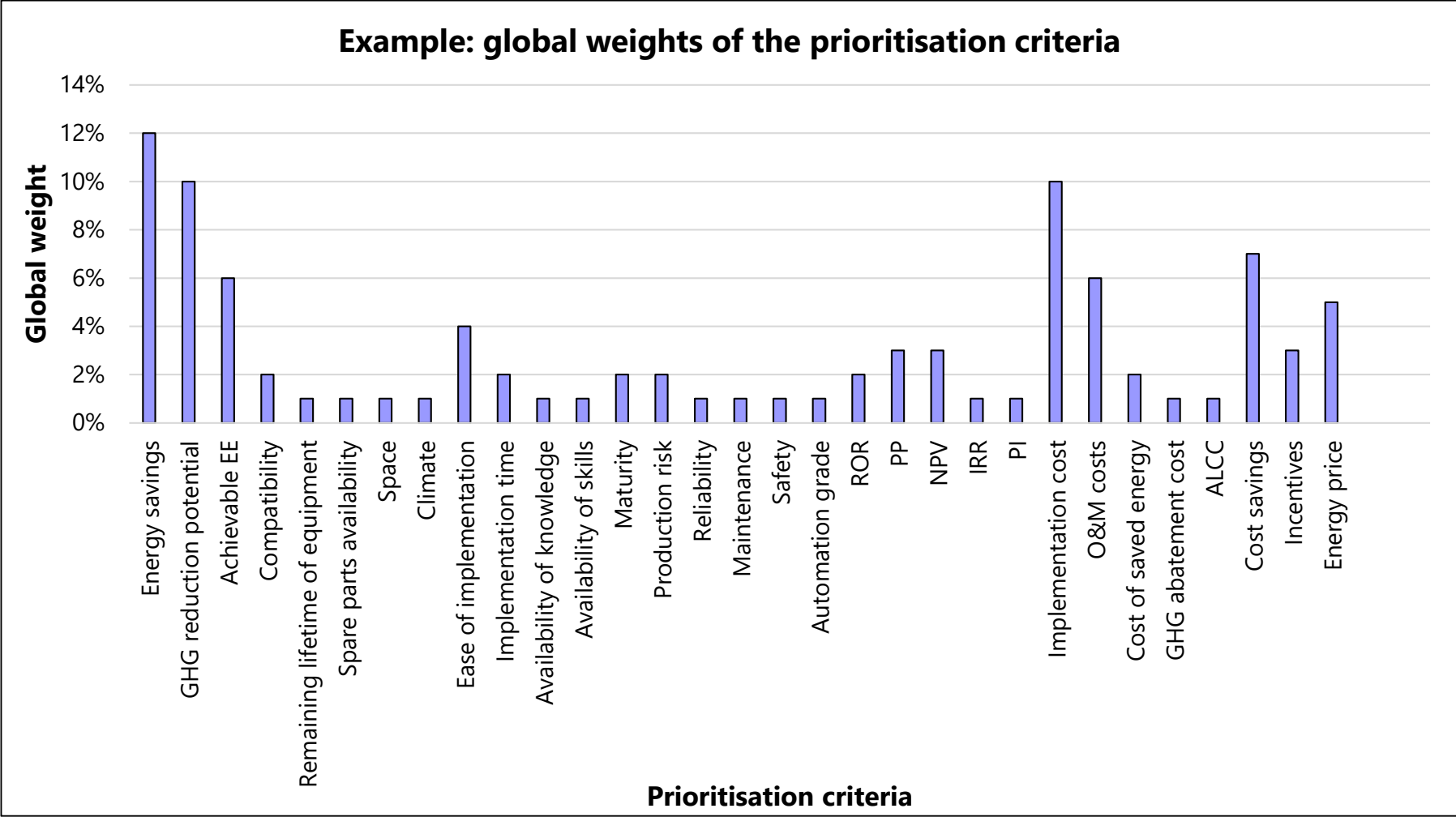


Figure 2-34: Example output of the global criteria weights obtained from the questionnaire.

Final prioritisation scores

After the assignment of local weights to each of the EEMs, the final prioritisation score of each EEM is calculated using Equation (8) in Section 2.5. The final prioritisation scores of all the Stage 2 EEMs sum to one due to the normalisation of the criteria ratings. However, the prioritisation score is expressed as a percentage to compare the contribution of each EEM to the goal, namely achieving EE. The implementation order of the EEMs is subsequently ranked according to their final prioritisation scores.

Consider an example to illustrate the process. Four EEMs, labelled A to D, are to be prioritised. Figure 2-35 shows an example of the final weight of each EEM relative to achieving the goal of EE. In this example, EEM A contributes the most to the goal of EE with a 40% weight. EEM B and EEM C contribute 30% and 20%, respectively. EEM D contributes the least of all the EEMs with a 10% contribution to the goal. It is recommended that EEM A be implemented first, followed by EEM B, EEM C and lastly EEM D.

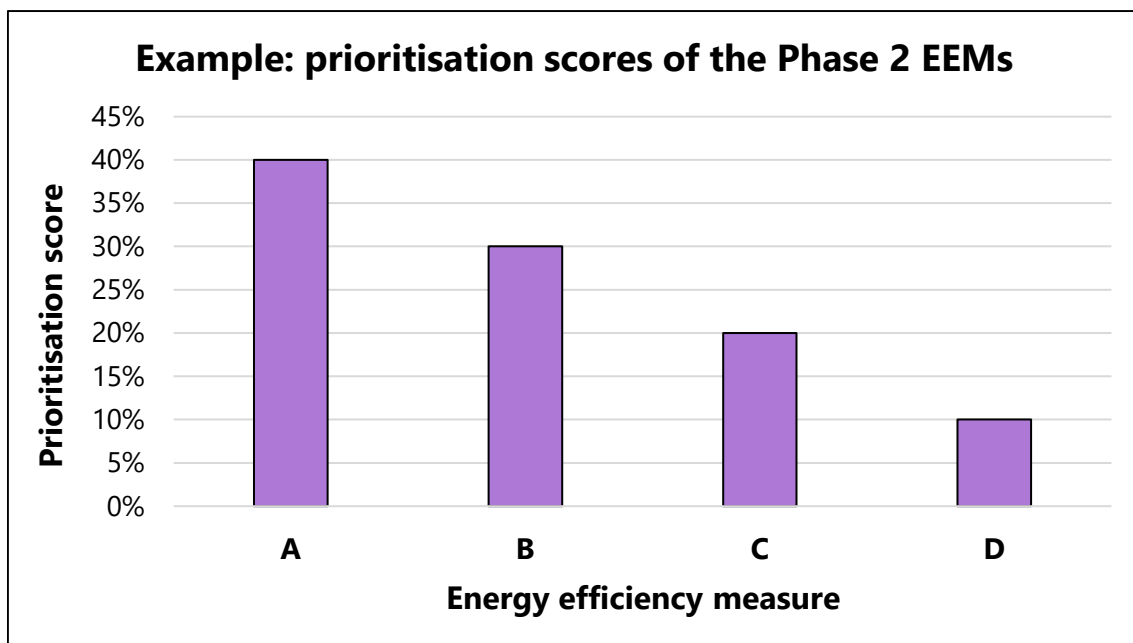


Figure 2-35: Example output of the prioritised Phase 2 EEMs.

Phase 2 conclusion

Phase 2 of the structured approach results in a prioritised list of feasible EEMs that passed through Phase 1. Prioritisation criteria are structured into a hierarchy and the criteria are weighted by pairwise comparisons via questionnaire (facilitated in Chapter 3). The questionnaire responses are

aggregated by the AIJ aggregation method, and the global weights of the prioritisation criteria are calculated.

The assigned global weights of the prioritisation criteria are analysed and compared to the findings from the criteria literature review in Section 2.3. A rating is assigned to each EEM with respect to each criterion and the local weight of each EEM with respect to each criterion is calculated through normalisation.

The final prioritisation score for each EEM is calculated by adding the product of the normalised ratings and the global criteria weights. The EEMs are ranked according to the final prioritisation score to yield a prioritised list of feasible EEMs.

A verification method for the structured approach is discussed in Section 2.7 to ensure that the requirements of the research objective were met.

2.7 Verification of the structured approach

The structured approach developed in Section 2.6 requires verification to ensure that the requirements of the research objective stated in Section 1.4 are met. The structured approach is verified by means of the checklist shown in Table 2-13.

Table 2-13: A checklist verifies that the study objective is met.

Requirement of research objective	Addressed by the structured approach
1. The approach considers available financial incentives as part of the analysis of EEMs.	Section 1.2.3 identified the use of incentives to address the <u>shortage of financial resources</u> barrier theme. Thus, incentives are considered in Stage 1 and Stage 3 of the feasibility assessment of Phase 1. Stage 1 consists of a high-level estimation of potential incentive benefits where Stage 3 considers the incentive calculations in more detail.
2. The approach systematically determines the technical and financial feasibility of EEMs.	<u>Project uncertainty</u> was identified as a major barrier theme in Section 1.2.3. Technical and financial feasibility assessments of the EEMs are used to reduce the project uncertainty. The feasibility of the EEMs is considered systematically in Phase 1 through three stages of feasibility

Requirement of research objective	Addressed by the structured approach
	assessments. Each stage is staggered to increase with time and effort. This is done to put EEMs less likely to be feasible on hold at an early stage. More effort is then only spent on projects with a higher likelihood of feasibility. This structure is designed to address the <u>limited time and human resources</u> barrier theme identified in Section 1.2.3.
3. The approach uses multiple criteria to prioritise the order in which the feasible projects should be implemented.	Phase 2 utilises multiple prioritisation criteria to rank the implementation order of the feasible EEMs. This is designed to address the <u>limited time and human resources</u> barrier theme identified in Section 1.2.3.

Table 2-13 verifies that the structured approach meets all three requirements of the research objective. Table 2-13 verifies that the structured approach links the research environment with the design process through the relevance cycle of the DSR methodology.

The structured approach is validated in Chapter 3 by applying it to a case study.

2.8 Conclusion

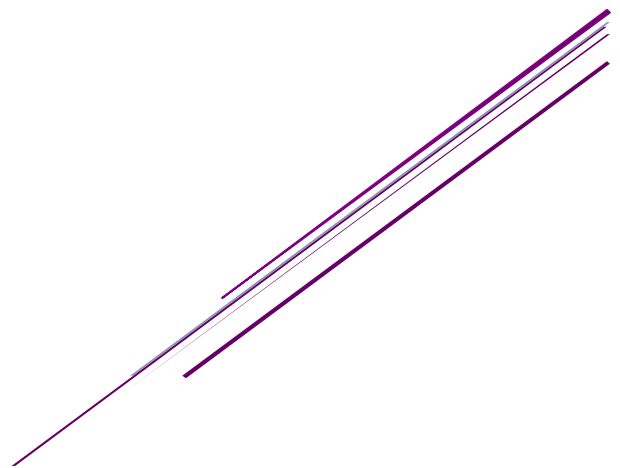
Chapter 2 discusses the development of a solution to the stated research objective. A review of the available EE incentives in South Africa is conducted in Section 2.2. Section 2.3 consists of a review of various feasibility criteria used in the evaluation of EEMs. The prioritisation criteria are reviewed and compiled in Section 2.4 and the AHP prioritisation method is illustrated in Section 2.5. Section 2.1 to Section 2.5 encompass the rigour cycle of the DSR methodology.

The structured approach is developed in Section 2.6. The structured approach consists of two phases, namely a feasibility assessment phase and a prioritisation phase. The feasibility assessment consists of three stages of evaluation that ultimately yield a list of feasible EEMs. The list of feasible EEMs is subsequently prioritised in the second phase of the structured approach. Section 2.6 represents the design cycle of the DSR methodology.

The structured approach is verified in Section 2.7 by means of a checklist addressing the requirements of the research objectives. Section 2.7 is included in the relevance cycle of the DSR research methodology since it relates the design of the artefact to the research environment.

CHAPTER 3:

RESULTS AND DISCUSSION



3 RESULTS AND DISCUSSION

3.1 Preamble

The structured approach designed in Chapter 2 is applied to a case study as a validation of the approach. Figure 3-1 shows a summary of the contents of Chapter 3. Chapter 3 consists of both the design and relevance cycles of the Design Science Research (DSR) methodology.

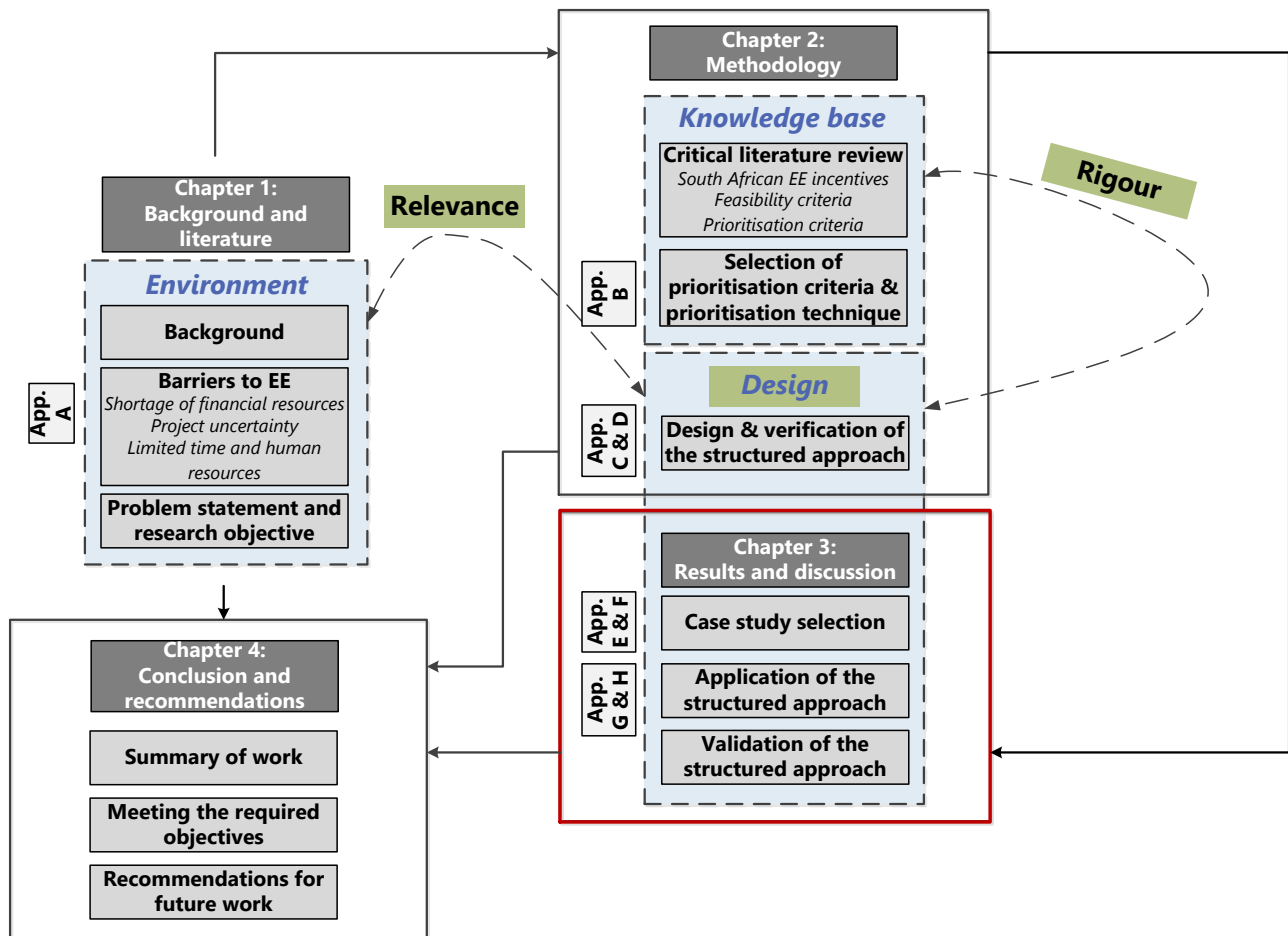


Figure 3-1: The structure of Chapter 3 within the research methodology.

Section 3.2 provides background on the selected case study and motivates the choice of the case study for validation of the structured approach. The structured approach is applied to the selected case study in Section 3.3. The results of the case study are validated in Section 3.4 before a conclusion to the chapter is provided in Section 3.5.

3.2 Case study selection

A large industrial facility that consists of various energy intensive activities is selected as the case study. The facility produces base chemicals and performance chemicals through integrated plants and manufacturing processes. The facility also produces various utilities, such as electricity and steam, for on-site consumption and support of the manufacturing processes.

The case study facility is one of many large South African industrial companies that have set ambitious emission reduction targetsⁱ. The case study facility is committed to reducing its carbon footprint by utilising lower carbon-intensive energy feedstock, renewable energy sources, and energy efficiency measures (EEMs). The facility aims to achieve its targets by implementing various initiatives.

The industrial facility chosen as the case study has a list of multiple proposed EEMs to contribute to the energy efficiency (EE) improvement target of the company. The list consists of 161 EEMs with varying levels of detail and quality of information provided for each of the initiatives. The list of proposed EEMs is available in Table E-1 in Appendix E. The proposed EEMs have been assigned generic names and descriptions to protect the privacy and anonymity of the facility.

The proposed case study EEMs are categorised according to the project classification presented in Figure 1-2 of Section 1.2.2. Figure 3-2 shows a summary of the EEMs classified according to project type. The majority of the proposed EEMs consist of supply-demand matching projects (24%) followed by process control initiatives (19%). Projects that utilise new technology account for 15% of the proposed EEMs while Heat recovery/Combined heat and power (CHP) projects account for 14% of the initiatives. Retrofitting and maintenance projects make up 11% and 9% of the EEMs, respectively. Minimising losses is the smallest category, representing only 7% of the proposed EEMs.

Despite some of the proposed initiatives on the list lacking estimated energy savings, total potential energy savings of 5.8 TWh per annum are estimated. Furthermore, cost savings of R1.1 billion are estimated from the available project information. The total energy and cost savings of the EEMs will be indicated throughout the application of the approach to further facilitate the discussion of the results.

ⁱ Centre for Environmental Rights. "Disclosing the metrics and targets used to assess and manage relevant climate-related risks and opportunities." fulldisclosure.cer.org.za. <https://fulldisclosure.cer.org.za/2019/findings/metrics-targets> (accessed Nov. 3, 2021).

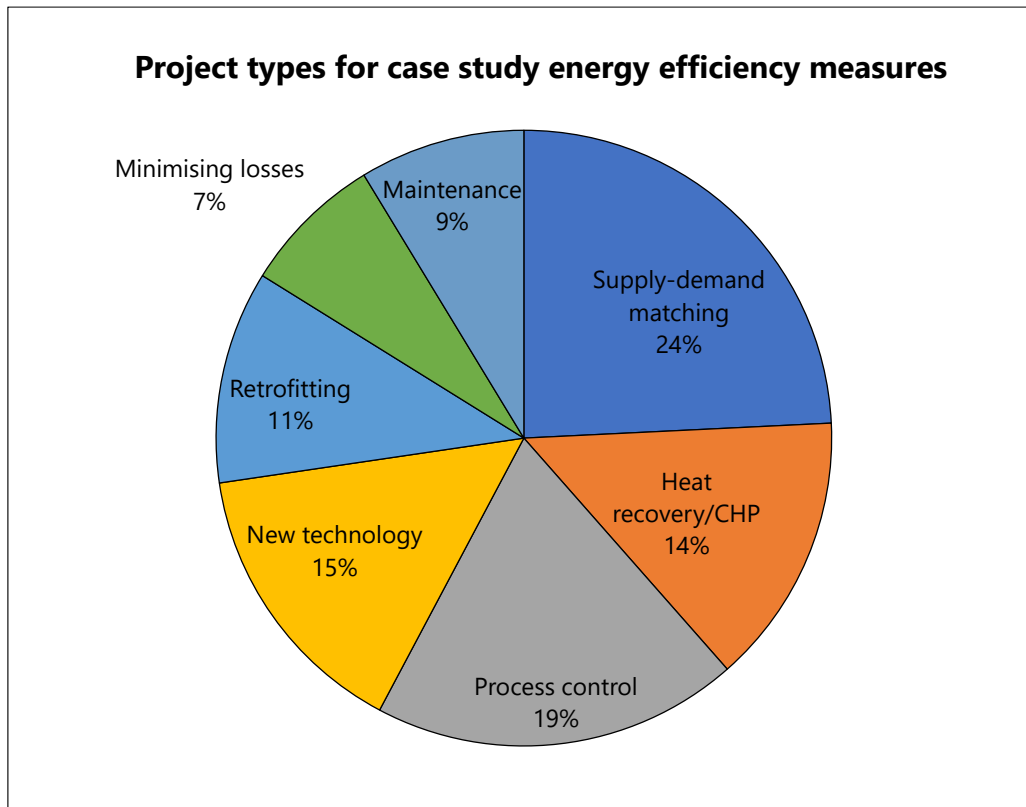


Figure 3-2: Classification of the case study EEMs according to project type.

Despite the [potential](#) for EE identified by the list of proposed EEMs, only a select number of initiatives from the list has been implemented to date. The full-scale implementation of all the identified 161 EEMs is therefore not a practical solution at the facility. This scenario is consistent with the problem statement and the common barriers to EE discussed in Chapter 1 are also applicable to this facility, namely that a shortage of financial resources, project uncertainty, and limited time and human resources have contributed to the low execution rate of the proposed EEMs.

The facility can therefore benefit from the structured approach designed in Chapter 2, since the multitude of EEMs can be evaluated for feasibility in a structured and systematic manner. The total implementation cost of the EEMs is high and thus the consideration of available incentives may alleviate the financial burden of implementing the proposed EEMs. Furthermore, since the facility may have limited time and human resources available, the feasible projects should be prioritised.

The structured approach was designed to categorise and label the proposed EEMs with similar characteristics in terms of their feasibility status or type of outstanding information. The structured categorisation and labelling of EEMs allow the quantification of the magnitude of energy savings (ES) and cost savings (CS) at each step of the structured approach. This may aid in the holistic energy

planning of the facility to ensure that it contributes to the overall EE improvement target of the company.

3.3 Application of the designed approach

The structured approach developed in Section 2.6 consists of two phases. The proposed EEMs were first evaluated by the three feasibility stages of Phase 1. The feasible EEMs were subsequently prioritised by Phase 2 of the structured approach. This is done to test if the developed approach can be used on a real-world case study. The results gathered in this process will also be compared to the actual implementation statuses at the facility to validate if the developed approach addresses the problem statement and research objective of this study.

The structured approach requires the weighting of various criteria by individuals with experience in energy management. A total of 22 individuals with qualifications ranging from bachelor's degrees to PhDs, and energy management experience between 2 and 26 years were selected to weight various criteria via questionnaire. A summary of the respondents' qualifications and energy management experience is shown in Table F-1 in Appendix F.1. The questionnaire shown in Appendix D was modified according to the information available for the criteria for this case study. The adapted questionnaire can be found in Appendix F.2.

The weighted criteria were used in both Phase 1 and Phase 2 of the structured approach. During Phase 1 of the structured approach, the results from the questionnaire were used to evaluate the technical complexity of EEMs. The weighted criteria resulting from the questionnaire were also utilised to prioritise the feasible EEMs in Phase 2 of the structured approach.

The results of applying Phase 1 and Phase 2 to the case study are discussed in Section 3.3.1 and Section 3.3.2, respectively.

3.3.1 Phase 1: Feasibility assessment

Phase 1 of the structured approach developed in Section 2.6.1 consists of three stages of feasibility assessments. The case study was evaluated by each stage of the feasibility assessment as discussed in the sections that follow.

Stage 1: Screening

Stage 1 of the structured approach was applied to the case study by assessing the availability of information and evaluating the high-level performance indicators. The results of applying each step of Stage 1 to the case study are shown in Figure 3-3 and are discussed in detail in the paragraphs that follow.

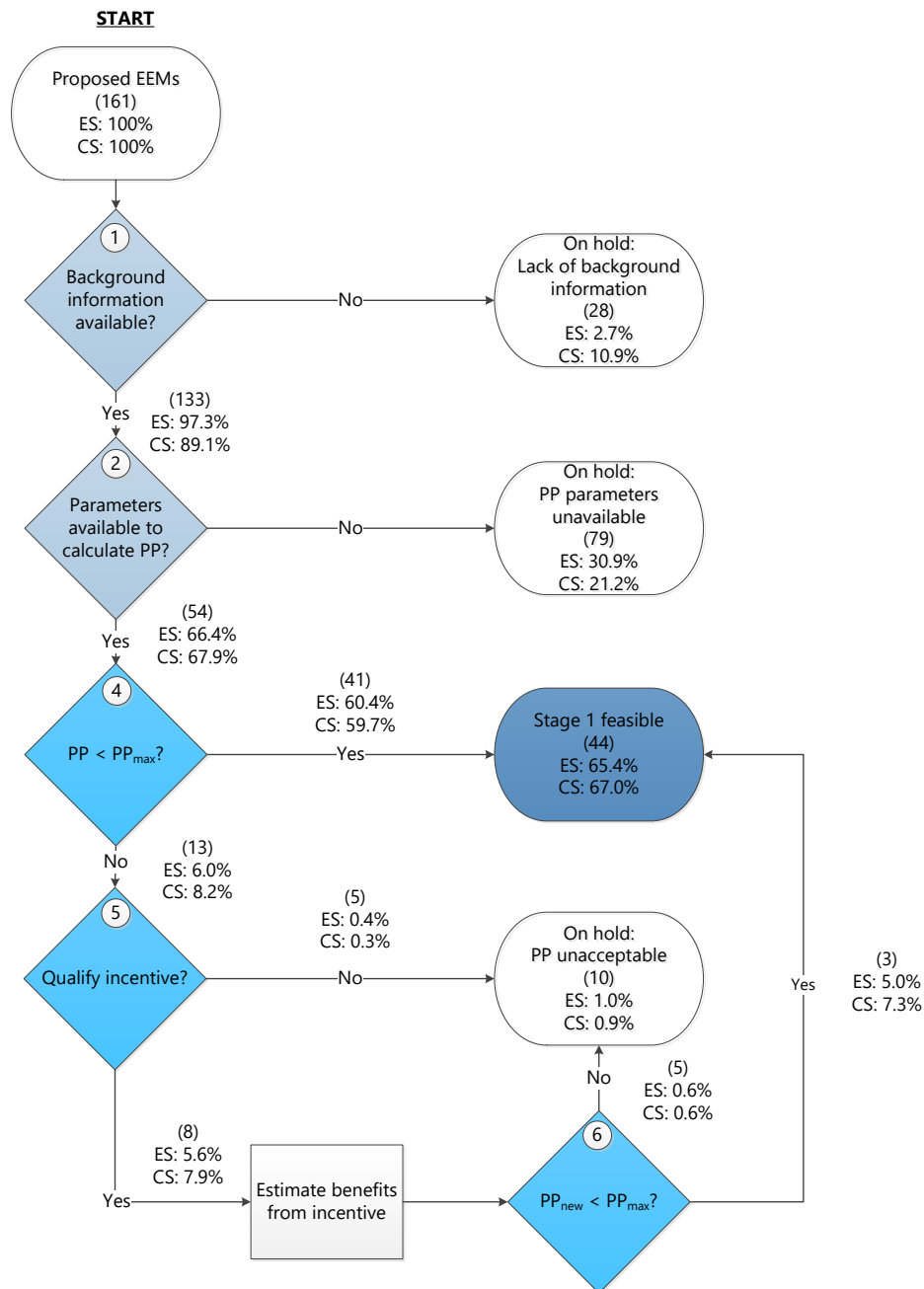


Figure 3-3: The results of the case study for Stage 1 of the feasibility assessment.

Since a short project description with some background information is crucial to assess the overall feasibility of an EEM, an assessment on the availability of information was conducted. The list of 161

proposed EEMs were evaluated individually to determine whether sufficient background information is available.

This process is illustrated by **Decision 1** of Figure 3-3 where 28 of the proposed EEMs did not have sufficient background information. Therefore, these 28 EEMs, accounting for 2.7% of the initial estimated energy savings and 10.9% of the initial estimated cost savings, were placed on hold due to a lack of background information.

The remaining 133 EEMs were evaluated by **Decision 2** to determine if the parameters required to calculate the payback period (PP) were available. A total of 79 of the EEMs did not have the required parameters to calculate the PP available and were therefore placed on hold. The 79 EEMs placed on hold accounted for 30.9% of the energy savings and 21.2% of the total cost savings.

The PPs of the remaining EEMs were assessed for suitability by **Decision 3** in Figure 3-3. The facility chosen for the case study has a maximum allowable PP (PP_{max}) of three years for EEMs on the list. Overall, 41 of the proposed EEMs had PPs less than PP_{max} and were deemed feasible by Stage 1 of the feasibility assessment. The 41 EEMs account for 60.4% of the total energy savings and 59.7% of the total cost savings. The remaining 13 projects, accounting for 6.0% of the total energy savings and 8.2% of the total cost savings, had PPs larger than PP_{max} .

The remaining 13 projects were assessed for the availability of incentives to possibly improve the business case above the threshold. Six (6) of the EEMs did not qualify for incentives and were placed on hold. The remaining 7 EEMs, accounting for 5.6% of the total energy savings and 7.9% of the total cost savings, qualified for incentives as shown by **Decision 5** in Figure 3-3.

The benefits from the incentives were estimated for the 7 EEMs. Four (4) of the EEMs, accounting for 0.6% of the energy savings and 0.6% of the cost savings, had unacceptable PPs despite the benefits calculated from the incentives. However, the estimated benefits of the incentives of 3 of the projects improved their PPs to less than PP_{max} . The 3 EEMs account for 5.0% of the total energy savings and 7.3% of the total cost savings.

Figure 3-4 illustrates the high-level categorisation of the proposed EEMs as a result of applying Stage 1 of the feasibility assessment to the case study. Figure 3-4 shows that approximately two thirds (66%) of the proposed EEMs were disregarded due to a lack of available information. This translates to roughly a third (34%) of both the total estimated energy savings and cost savings (32%).

There is therefore significant potential for the implementation of more EEMs if the outstanding information can be gathered from the relevant project owners.

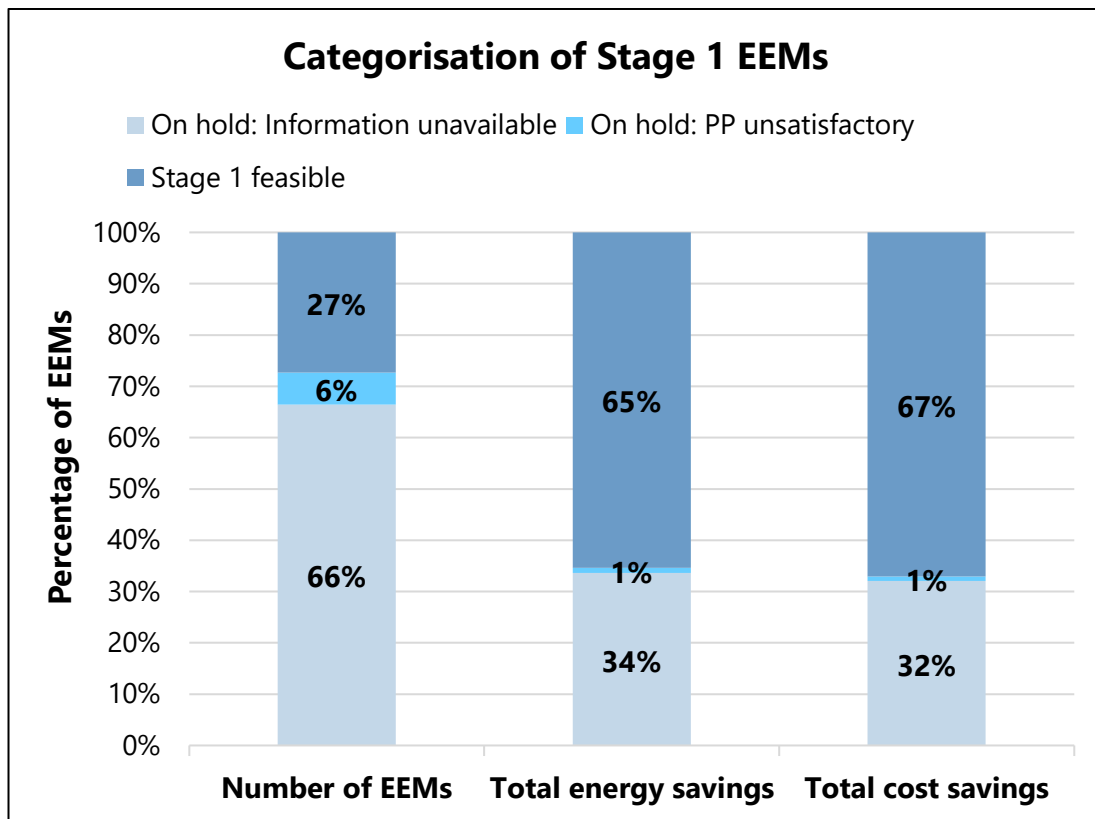


Figure 3-4: The high-level categorisation of the case study results from Stage 1.

Initially, 8% of the proposed EEMs did not have acceptable PPs. However, due to a high-level assessment of available incentives, 2% of the EEMs were found to have acceptable PPs if the estimated incentive benefit is included. Without the consideration of incentives, these 3 EEMs, accounting for 5% of the total energy savings and 7% of the total cost savings, would have been discounted due to unacceptable PPs.

Stage 1 summary

Figure 3-5 shows the summarised results of the case study for Stage 1 of the feasibility assessment. Figure 3-5 shows that the almost two thirds of the proposed EEMs were placed on hold due to a lack of available information. The 107 EEMs placed on hold account for 33.6% of the total available estimated energy savings and 32.1% of the total cost savings. Figure 3-5 further shows that a total of 10 EEMs were placed on hold due to unacceptable PPs. The 10 projects account for 1.0% of the total energy savings and 0.9% of the total cost savings.

Furthermore, 54 of the proposed EEMs had the required information available and the simple PP of these EEMs could be calculated. Ultimately, 44 EEMs passed the first stage of the feasibility assessment. Thus, approximately 65% of the total energy savings and 67% of the total cost savings were deemed Stage 1 feasible.

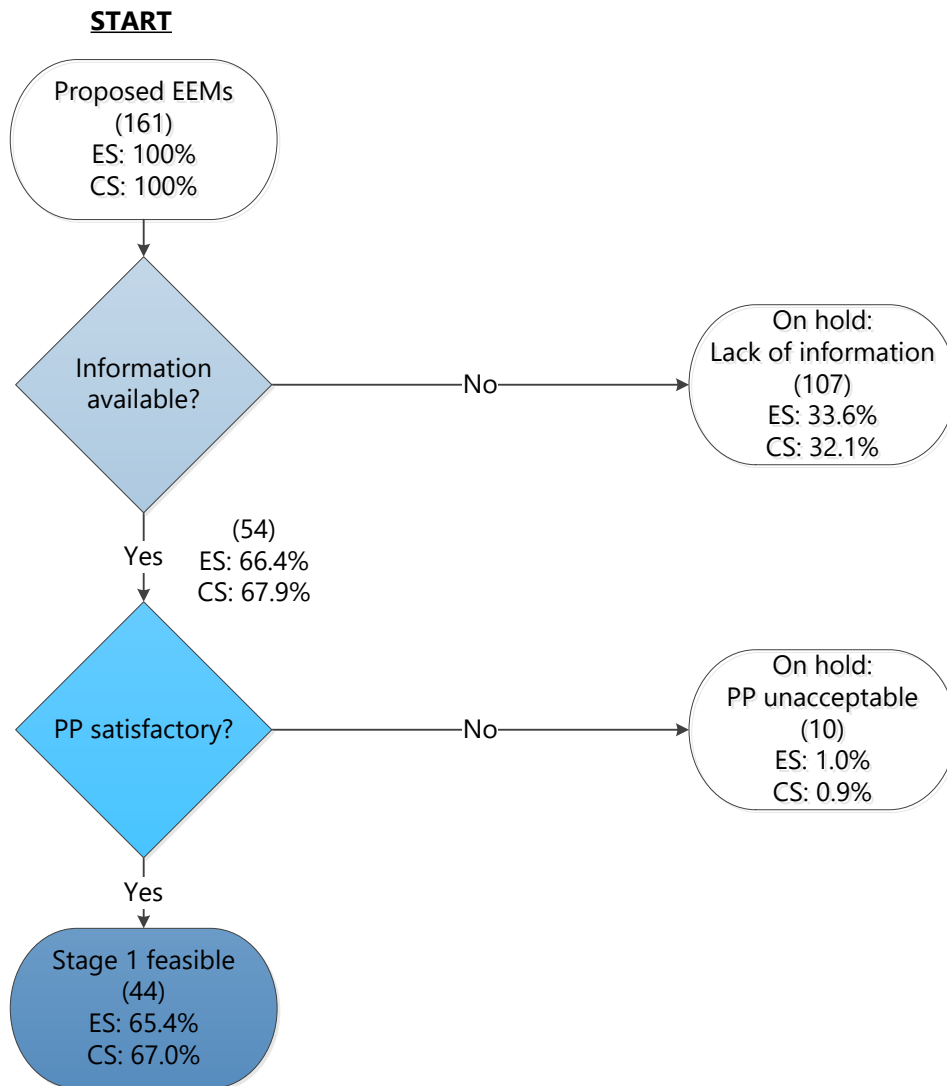


Figure 3-5: A summary of the results for Stage 1 of the feasibility assessment.

The 44 EEMs, amounting to 27% of the proposed EEMs, that were deemed feasible by Stage 1 of the feasibility assessment, progressed to Stage 2.

Stage 2: Technical feasibility

Overall, a total of 27% of the proposed EEMs passed Stage 1 of the feasibility assessment. The technical complexity of the 44 EEMs was assessed before the technical feasibility of the EEMs was evaluated. The assignment of the complexity level and the subsequent technical feasibility assessment are discussed in the sections that follow.

Complexity level

Information on all the technical *Complexity* criteria from the review in Section 2.3.1 was not available for all the proposed EEMs. Therefore, the *Complexity* criteria for which information was available were chosen for this case study and are shown in Figure 3-6.

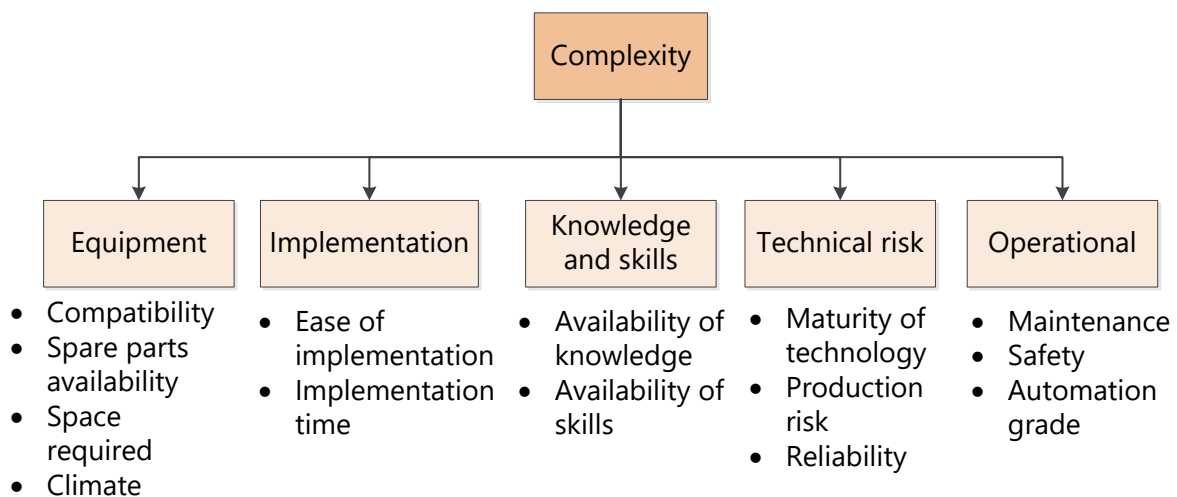


Figure 3-6: The *Complexity* criteria selected for the case study (adapted from Figure 2-18).

As is common with MCDM problems, each of the technical criteria are not equally weighted and the assignment of weights to the criteria was necessitated. Weights were assigned to the criteria by pair-wise comparisons of each level of the hierarchy according to the Analytical Hierarchy Process (AHP) procedure outlined in Section 2.5.

Pair-wise comparisons were made via questionnaire by individuals with energy management experience. The weighting of the complexity criteria by the 22 respondents was accomplished by completing Table F-6 to Table F-11 of the questionnaire in Appendix F.

The global weight of each criterion was determined according to the procedure explained in Step 3 of Section 2.5. The individual judgements made by each of the respondents were aggregated by taking the geometric mean of the individual weights assigned [121]. The aggregated judgement matrices for the complexity criteria are shown in Table G-1 to Table G-6 in Appendix G.1. The global weights assigned to the complexity criteria by the questionnaire respondents are shown in Figure 3-7.

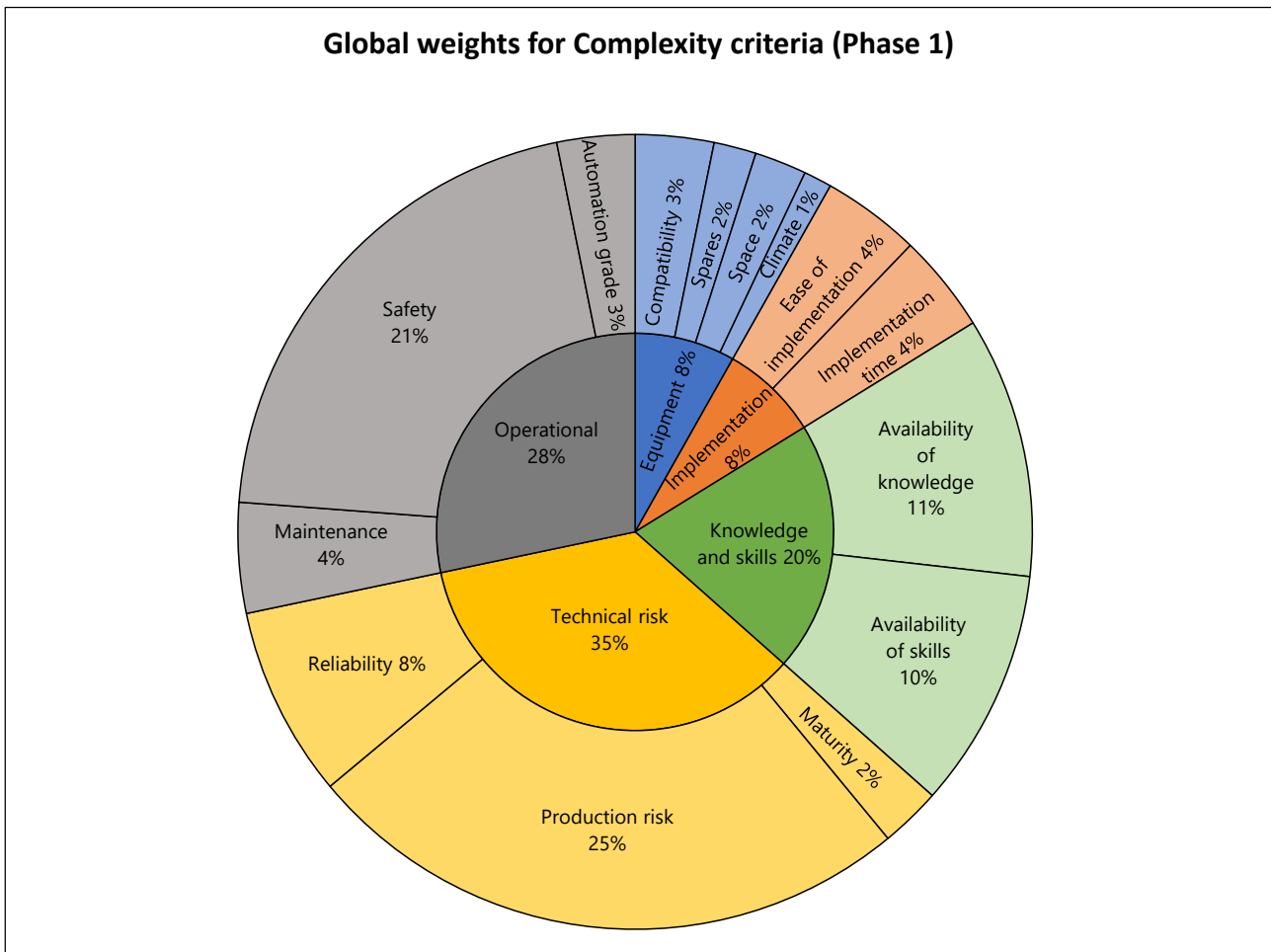


Figure 3-7: The global weights assigned to the *Complexity* criteria via questionnaire.

Figure 3-7 shows that the respondents to the questionnaire regard the *Technical risk* category as the most important complexity category, contributing to 35% of the total complexity weight. This validates the literature review of technical criteria conducted in Section 2.3.1 where the criteria comprising the *Technical risk* category were the most referenced complexity criteria.

The *Operational* category was weighted as second most important, contributing to 28% of the total complexity weight, followed by the *Knowledge and Skills* category contributing to 20% of the total complexity weight. This validates the literature review of technical criteria conducted in Section 2.3.1

where the criteria comprising the *Operational* and *Knowledge and Skills* categories are referenced in at least 10% of the reviewed sources.

The *Equipment* and *Implementation complexity* categories were scored as the least important by the respondents, both with respective weights of 8% of the total complexity. This is also a validation of the findings from the literature review conducted in Section 2.3.1 where the criteria comprising these categories were referenced in less than 10% of the consulted studies.

Overall, *Production risk* is regarded as the most important complexity criterion while *Climate* is regarded as the least important criterion. This is corroborated by the findings of the literature review in Section 2.3.1 where *Production risk* is referenced in 23% of the reviewed sources while *Climate* is referenced in only 3% of the sources.

Using the weighted criteria, complexity scores were assigned to the EEMs that progressed to Stage 2 of the feasibility assessment. Since most of the *Complexity* criteria are qualitative, the complexity ratings scale outlined in Table 2-9 was used to assign complexity ratings. Although *Implementation time* is a quantitative criterion, only estimations, e.g. less than one year, are provided. Therefore, a ratings scale was also used to assign ratings to each of the EEMs based on their estimated ranges of implementation times.

A value of between 1 and 3 was assigned to each of the EEMs with respect to each criterion. Since the higher rating should reflect the greater convenience with regards to the alternatives, a value of 3 indicates low complexity and a value of 1 indicates high complexity with regards to the criterion. The complexity scores assigned to each of the EEMs for each of the complexity criteria are shown in Table G-7 in Appendix G.2.

After the assignment of scores to each complexity criterion, the complexity score of each EEM relative to each criterion was normalised. The final complexity score of each EEM was calculated by multiplying the normalised complexity score relative to each criterion with the global weight of the criterion.

Figure 3-8 shows the final complexity score of the remaining 44 EEMs, sorted according to increasing order of complexity (a higher final complexity score indicates a less complex project). EEM ID 58, with a final complexity score of 0.027, was found to be the least complex. EEM ID 161 was found to be the most complex with a final complexity score of 0.017.

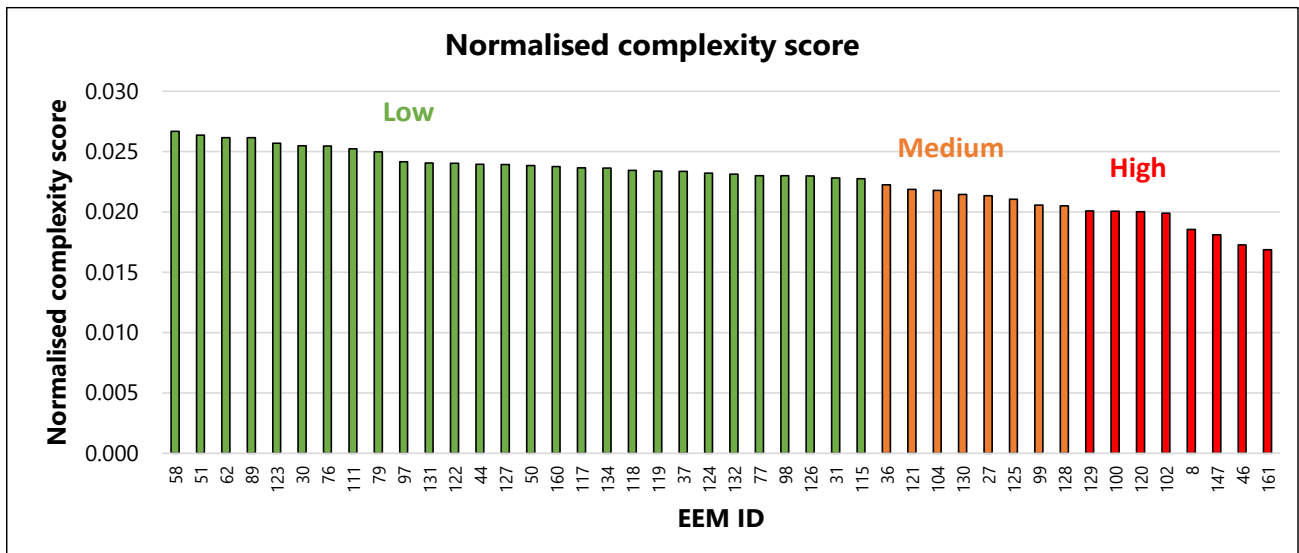


Figure 3-8: The final complexity scores for the remaining EEMs of the case study.

The EEMs were grouped according to their complexity scores to allow the labelling of the EEMs as *High*, *Medium*, or *Low* complexity. The interval between the three complexity levels was calculated as ≈ 0.003 . *High* complexity status was therefore assigned to EEMs with a final complexity score between 0.017 and 0.020. *Medium* complexity status was assigned to EEMs with a final complexity score between 0.020 and 0.023. *Low* complexity status was assigned to EEMs with a final complexity score between 0.023 and 0.027.

The complexity level assigned to each Stage 2 EEM is shown in Table G-8 in Appendix G.3. Overall, 19 of the EEMs were classified as *Low* complexity, as indicated in green on Figure 3-8. Furthermore, 17 of the EEMs were classified as *Medium* complexity, as indicated in orange on Figure 3-8. Eight (8) of the EEMs were classified as *High* complexity, as shown in red on Figure 3-8.

Based on the assigned complexity level, the technical feasibility of each EEM was evaluated.

Technical feasibility

After the classification of the EEMs according to technical complexity, the technical feasibility of the Stage 2 EEMs was determined. The technical feasibility was first assessed by determining whether a satisfactory method of verification (MOV) exists for each of the EEMs, as shown by **Decision 1** in Figure 3-9. The minimum MOV required from Table 2-12 based on complexity level was used. The MOV for the Stage 2 EEMs is shown in Table G-8 in Appendix G.3.

Decision 1 in Figure 3-9 shows that the list of EEMs did not provide a MOV for 5 of the EEMs. Approximately 24% of the total energy savings and 24.4% of the cost savings were lost at this step

of the feasibility assessment. If a suitable MOV can be provided for these measures, the facility may be able to achieve significantly more energy savings and cost savings.

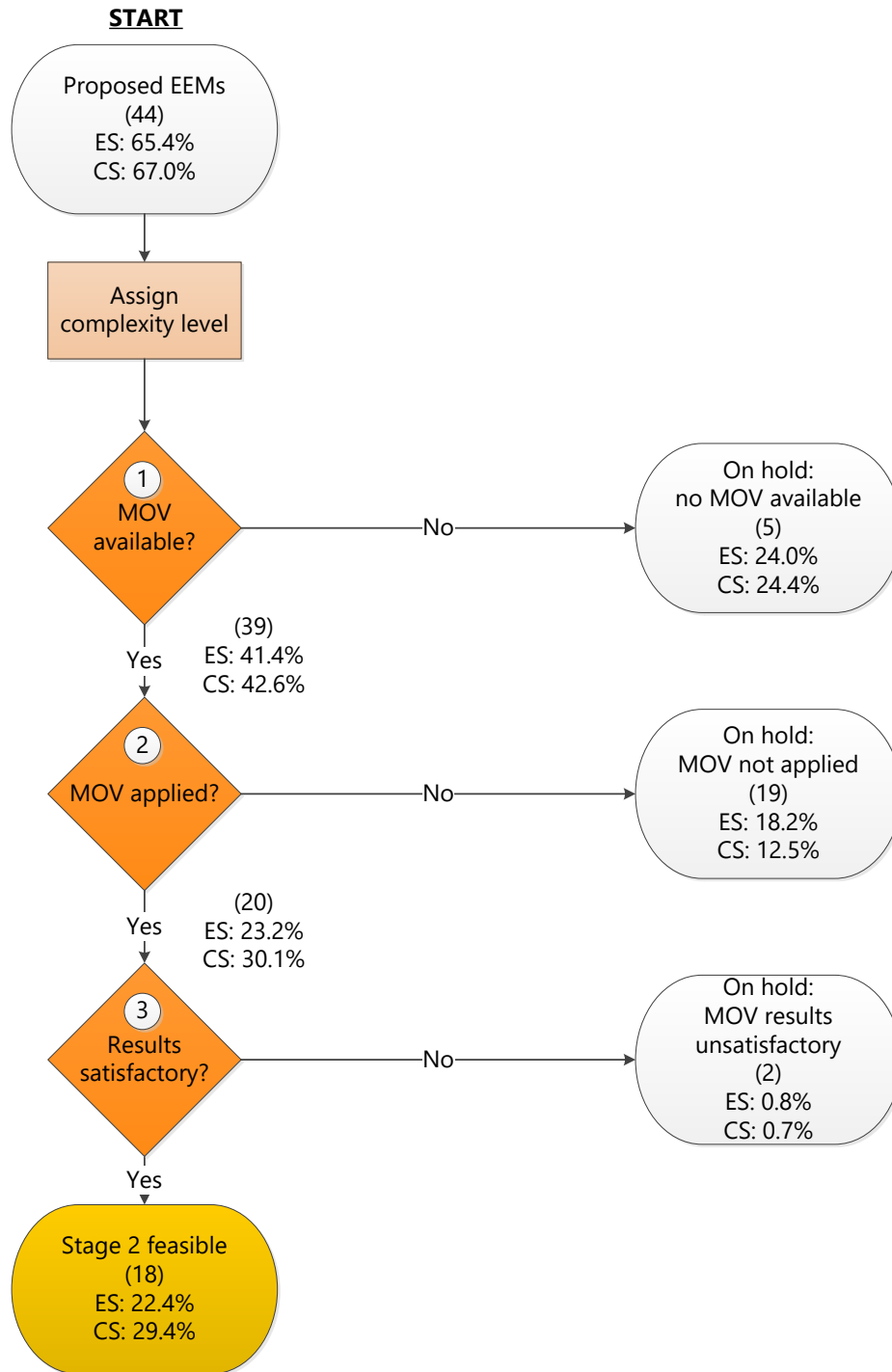


Figure 3-9: The results of the case study for Stage 2 of the feasibility assessment.

The remaining 39 EEMs proceeded to **Decision 2** in Figure 3-9 where 19 EEMs were placed on hold since these measures have not yet been technically verified. Approximately 18% of the total energy

savings and 12.5% of the total cost savings were placed on hold at this step. There is thus significant potential if the available verification methods are applied to the 19 EEMs.

The remaining 20 EEMs proceeded to **Decision 3** in Figure 3-9 where 2 EEMs were placed on hold due to unsatisfactory results obtained when the MOV was applied. The remaining 18 EEMs had satisfactory outcomes from the technical assessment and thus were deemed technically feasible.

Figure 3-10 illustrates the high-level categorisation of the proposed EEMs as a result of applying Stage 2 of the feasibility assessment to the case study. Figure 3-10 shows that 3% of the total initial EEMs were discounted due to an unavailable MOV. This amounts to 24% of both the total energy savings and cost savings that may be recovered if suitable MOV are assigned to these EEMs. The available MOV had not been applied to 12% of the total EEMs, resulting in 18% of the total energy savings and 12% of the cost savings being placed on hold. Therefore, a significant amount of the total energy savings may be achieved by testing the technical performance of these EEMs.

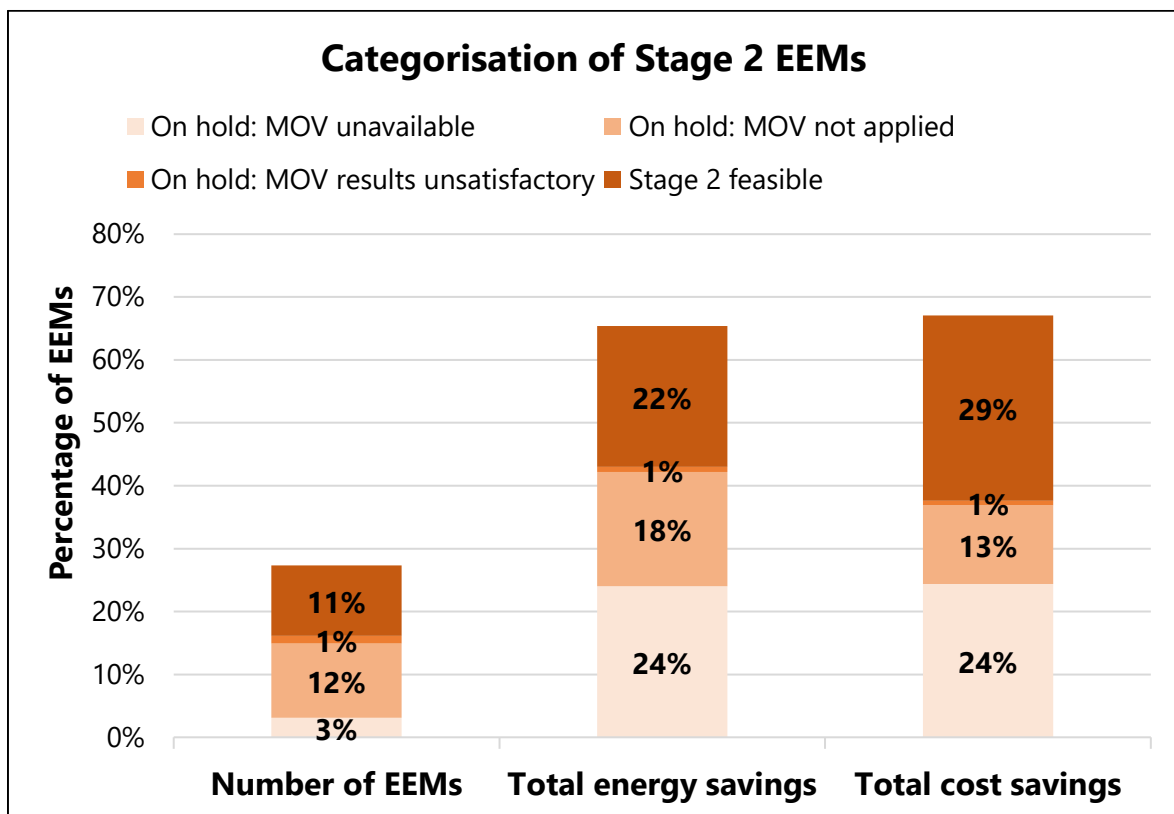


Figure 3-10: The high-level categorisation of the case study results from Stage 2.

Less than 1% of the total initial EEMs were disregarded due to unsatisfactory performance when applying the MOV. These EEMs account for less than 1% of the total energy savings and cost savings. 11% of the total EEMs had satisfactory outcomes when applying the MOV. Thus, only 22.4% of the

total energy savings and 29% of the total cost savings have proceeded through the first two stages of the feasibility assessment.

Stage 2 summary

Figure 3-11 summarises the results of the Stage 2 feasibility assessment applied to the case study. Figure 3-11 shows that 43% of the total energy savings and roughly 38% of the cost savings are lost due to the inability to prove that the EEMs are technically feasible. This validates the finding from Section 1.3 that project uncertainty is a major barrier to EE.

Figure 3-11 shows that ultimately 18 of the 44 EEMs that were evaluated by Stage 2 were deemed feasible. The 18 Stage 2 feasible EEMs account for 22.4% of the total energy savings and 29.4% of the total cost savings. The 18 EEMs that were deemed feasible by Stage 2 progressed to Stage 3 of the feasibility assessment.

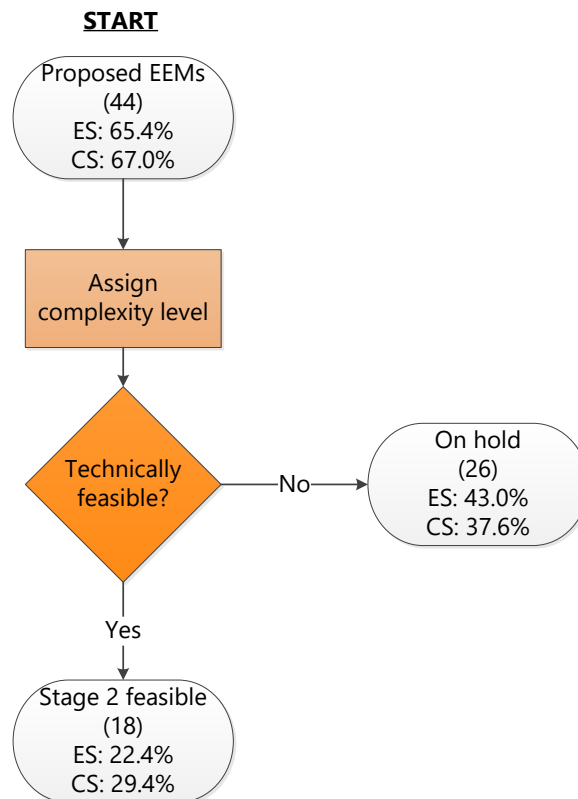


Figure 3-11: A summary of the results for Stage 2 of the feasibility assessment.

Stage 3: Financial feasibility

A total of 18 of the initial 161 EEMs progressed through Stage 1 and Stage 2 of the feasibility assessment and are evaluated by Stage 3. The eligibility of the remaining EEMs for incentives was evaluated as shown by **Decision 1** in Figure 3-12.

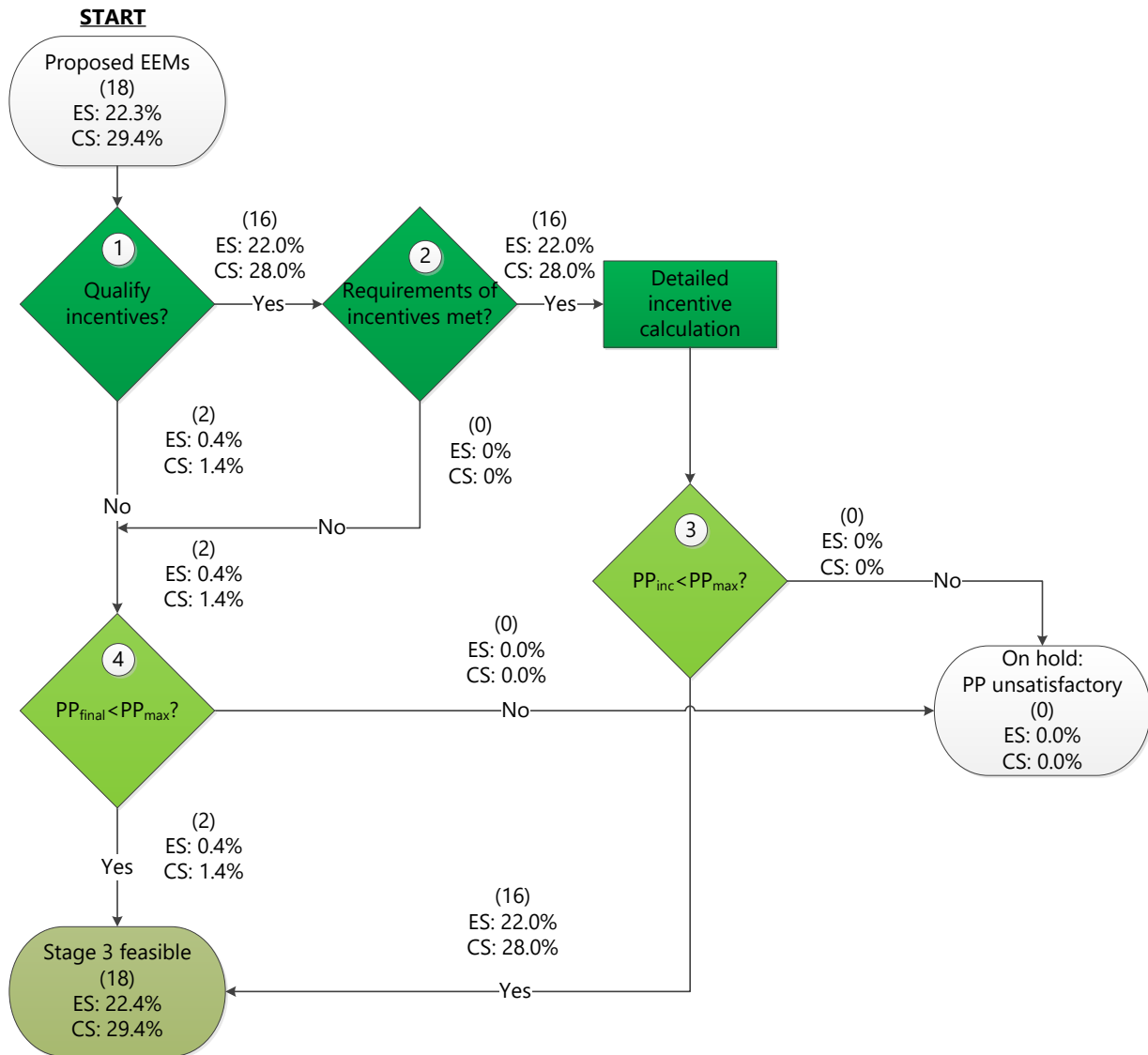


Figure 3-12: The results for Stage 3 of the feasibility assessment.

Sixteen (16) of the EEMs qualified for incentives, specifically the Section 12L tax incentive. Since the facility has a high level of data availability and quality due to an extensive metering programme, it was assumed that all 16 EEMs would meet the Measurement and Verification (M&V) requirements for the tax incentive, shown by **Decision 2** of Figure 3-12.

The incentive benefit for each of the 16 EEMs was calculated and the new PPs were evaluated by **Decision 3** in Figure 3-12. All 16 EEMs had satisfactory PPs and are deemed Stage 3 feasible. The 16 EEMs account for 22.0% of the total energy savings and 28.0% of the total cost savings.

The total cost savings for the 16 EEMs amount to approximately R316 million. The added benefits from the Section 12L tax incentive calculations are estimated at a R1 206 million tax certificate value. At a company tax rate of 28%, this amounts to R338 million in shareholder value. In this case study,

the utilisation of tax incentives may therefore lead to a total monetary benefit of double the estimated cost savings of the 16 EEMs.

The estimated implementation cost for the 16 EEMs that qualified for incentives is R718 million. The total incentive benefits for the 16 EEMs amount to 47% of the total implementation cost. Thus, if the Section 12L application were successful, nearly half of the total implementation cost for the 16 EEMs would be recovered. It is evident that the utilisation of incentives may greatly aid in funding high capital cost projects.

Two (2) of the 18 EEMs did not qualify for any incentives and thus the financial feasibility of the EEMs was determined by evaluating the PP from Stage 1 of the feasibility assessment. The final PP of the two EEMs was evaluated as shown by **Decision 4** in Figure 3-12. Both EEMs had acceptable PPs and were thus deemed feasible by Stage 3 of the feasibility assessment. The 2 EEMs account for 0.4% and 1.4% of the total energy savings and total cost savings, respectively.

Figure 3-13 illustrates the high-level categorisation of the proposed EEMs as a result of applying Stage 3 of the feasibility assessment to the case study. Figure 3-13 shows that all the Stage 3 EEMs were found to be financially feasible.

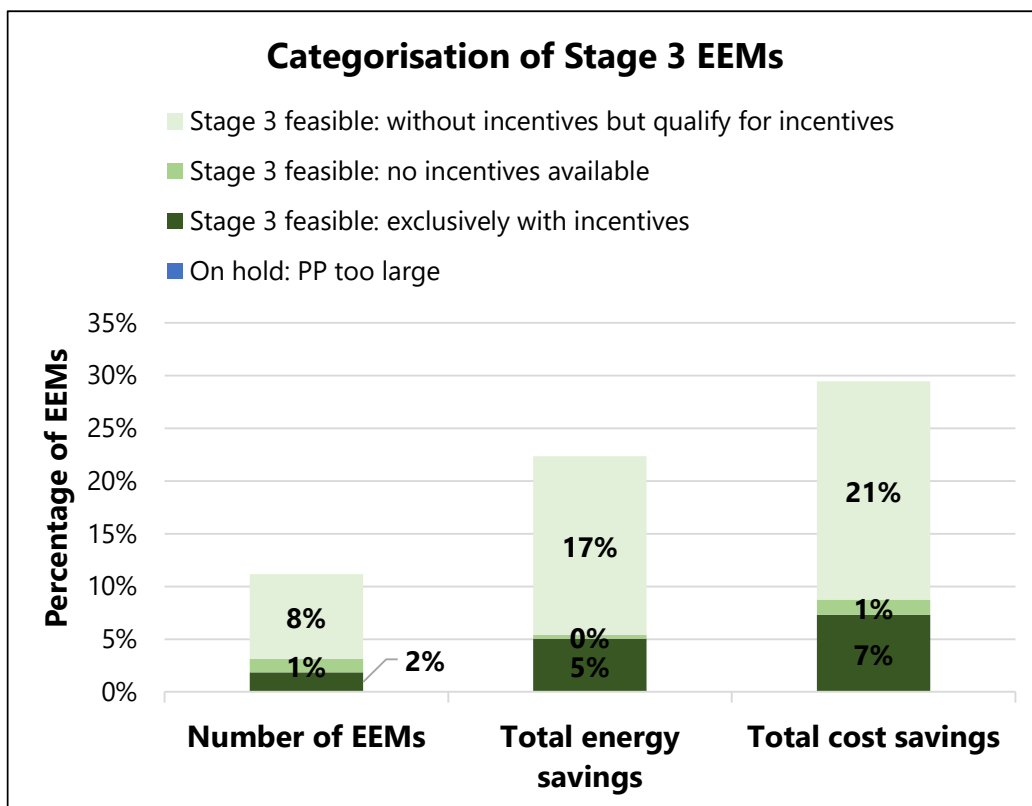


Figure 3-13: The high-level categorisation of the case study results from Stage 3.

Overall, 9% of the initial EEMs were feasible without the consideration of incentives, even though these measures did qualify for incentives. These EEMs represent 17% of the total energy savings and 22% of the total cost savings. Figure 3-13 shows that 1% of the EEMs did not qualify for incentives but were nonetheless financially feasible. These EEMs account for less than 1% of both the total energy savings and cost savings.

A total of 9% of the initial EEMs were thus found to be financially feasible regardless of the incentive qualification status. These EEMs account for 17% of the energy savings and 22% of the cost savings. The total estimated benefits from the incentives for these EEMs are double the cost savings.

Figure 3-13 furthermore shows that 2% of the initial EEMs are not feasible without the utilisation of incentives. Thus, 5% of the total energy savings and 7% of the total cost savings would have been prematurely dismissed if incentives were not considered.

Stage 3 summary

Figure 3-14 provides a summary of the results for Stage 3 of the feasibility assessment. The detailed incentive analysis estimated that the successful utilisation of the Section 12L tax incentive may yield incentive benefits that are double the cost savings and 47% of the total implementation cost of the qualifying EEMs. Furthermore, 5% of the total energy savings and 7% of the total cost savings would have been neglected without the consideration of incentives. The final list of 18 EEMs amount to 1.3 TWh of estimated energy savings.

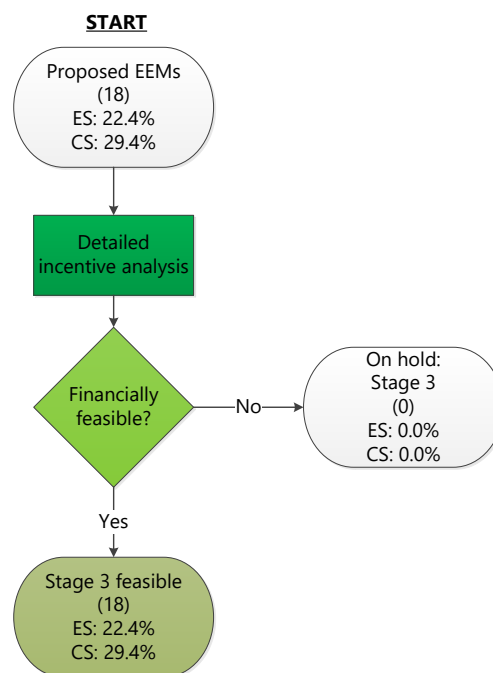


Figure 3-14: A summary of the results of the case study for Stage 3 of the feasibility assessment.

The case study thus proves that there is significant value in the consideration of incentives as part of the feasibility assessment. Following the detailed incentive analysis, all 18 of the EEMs that were evaluated by Stage 3 were deemed feasible.

Phase 1 conclusion

Phase 1 of the structured approach, consisting of the three stages of feasibility assessment, was applied to the case study. Figure 3-15 summarises the results of applying Phase 1 of the structured approach to the case study.

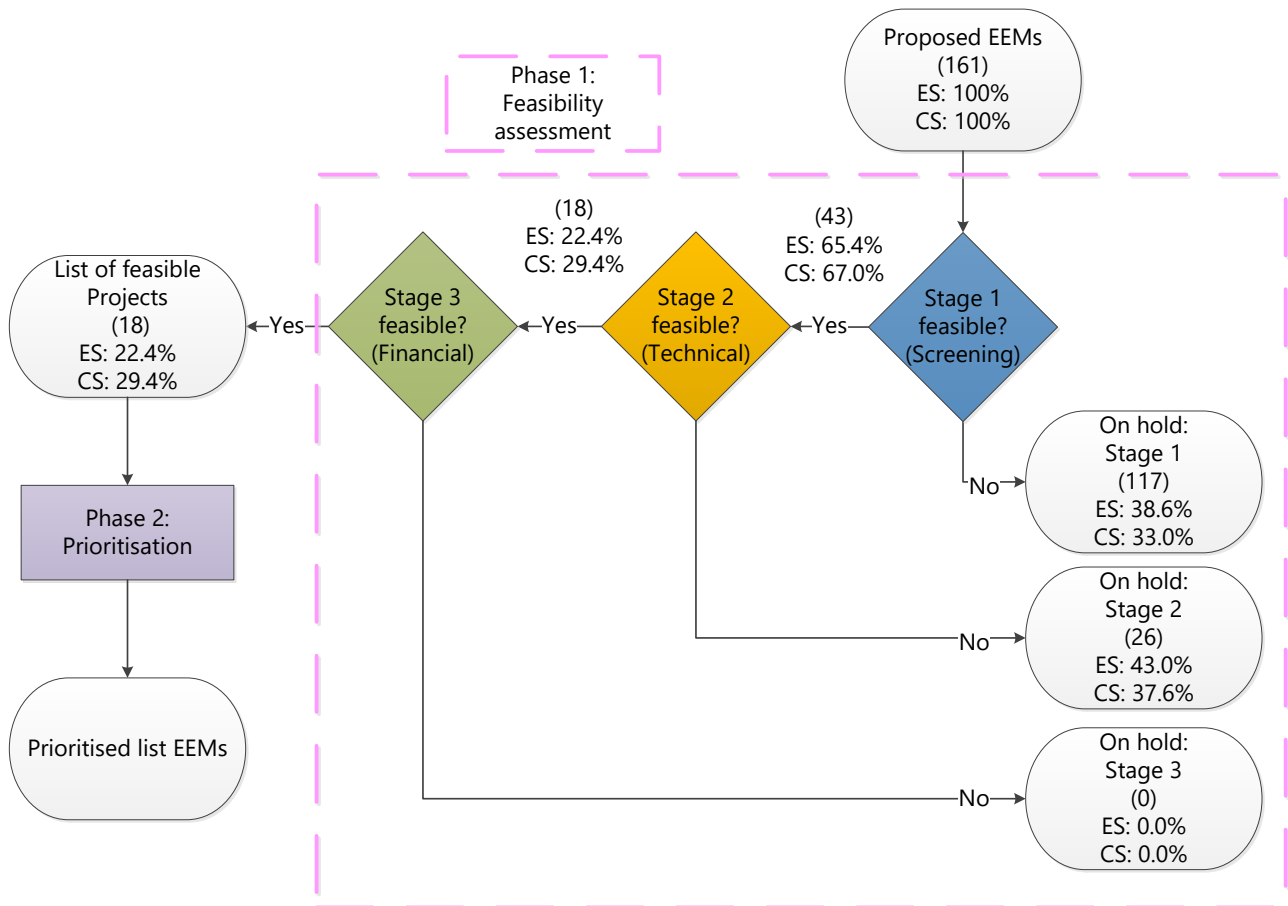


Figure 3-15: A summary of the results of the case study for Phase 1 of the structured approach.

A total of 117 of the 161 EEMs were placed on hold after the Stage 1 feasibility assessment. The EEMs that were placed on hold at Stage 1 account for 38.6% of the total energy savings and 33.0% of the total cost savings. Furthermore, 43 of the EEMs, accounting for 65.4% of the total energy savings and 67.0% of the total cost savings, proceeded to Stage 2 of the feasibility assessment.

Stage 2 of the feasibility assessment involved the assignment of complexity scores before the technical feasibility of the EEMs was evaluated. Complexity scores were assigned to the EEMs through

the weighting of complexity criteria by energy management experts via questionnaire. Based on the assigned complexity scores, the technical feasibility of the EEMs was evaluated by considering whether a satisfactory MOV was supplied and applied to each of the EEMs. Consequently, 26 of the remaining EEMs were placed on hold at Stage 2 of the feasibility assessment. The 26 EEMs account for 43.0% of the total energy savings and 37.6% of the total cost savings.

The remaining 18 EEMs proceeded to Stage 3 of the feasibility assessment. The EEMs were evaluated for qualifying incentives and 16 of the EEMs were found to most likely qualify for the Section 12L tax incentive. The shareholder value of the tax incentive is estimated to be equivalent to the total cost savings and half of the implementation cost of the qualifying EEMs. Following the detailed incentive analysis, all 18 EEMs were found to be feasible by Stage 3 of the feasibility assessment.

Overall, 18 of the initial 161 EEMs were deemed feasible overall since these measures passed all three stages of the feasibility assessment. The 18 EEMs account for 22.4% of the total energy savings and 29.4% of the total cost savings.

Figure 3-16 shows the classification of the EEMs that were placed on hold during Phase 1 according to project type. All the EEMs evaluated by Stage 3 were considered feasible and thus no EEMs were placed on hold at Stage 3. Most of the project types placed on hold at Stage 1 and Stage 2 show good agreement with the overall distribution of the proposed EEMs.

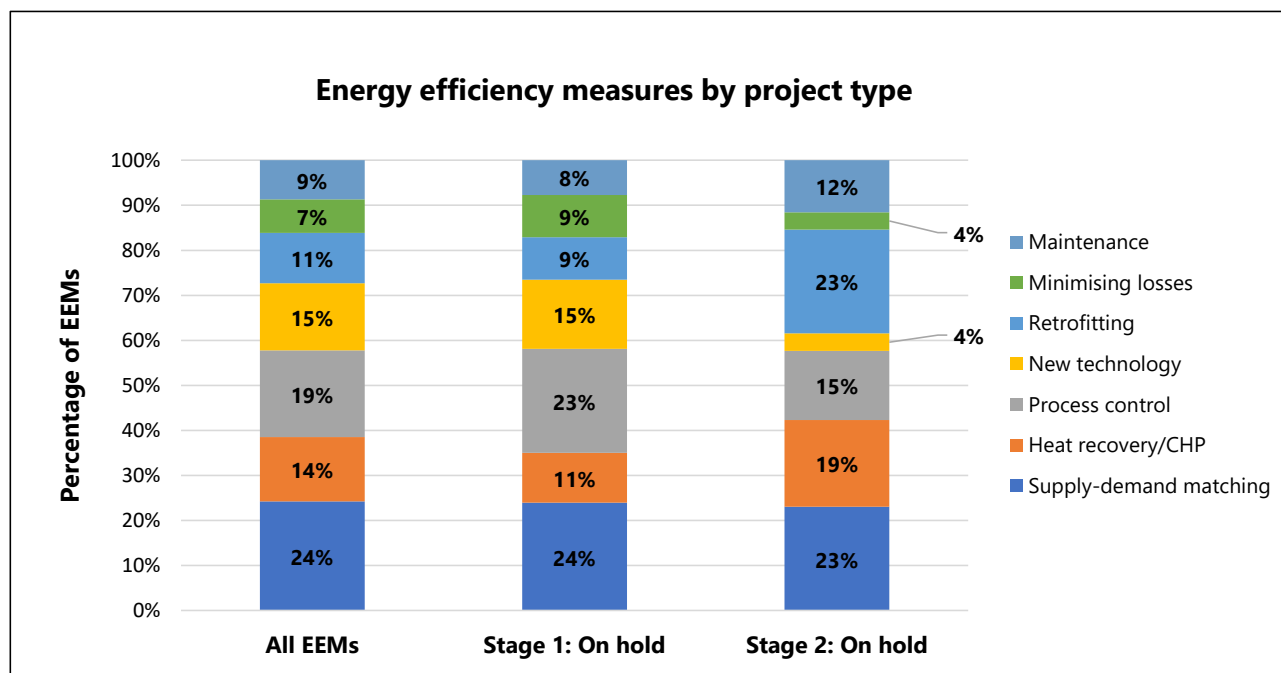


Figure 3-16: Categorisation of the EEMs placed on hold.

Process control EEMs account for 23% of the EEMs placed on hold during Stage 1. This is slightly more than the 19% process control EEMs that comprise all the proposed EEMs. Thus, process control EEMs are more frequently discounted during the screening stage than expected. It is thus concluded that process control EEMs may have less information available and/or unsatisfactory PPs compared to the other project categories.

Heat recovery/CHP EEMs account for 19% of the EEMs placed on hold during Stage 2. This is slightly more than the 14% heat recovery/CHP EEMs that comprise all the proposed EEMs. Thus, heat recovery/CHP EEMs are more frequently discounted during the technical feasibility stage than expected. It is thus concluded that heat recovery/CHP EEMs may be more technically complex than other project categories.

With the conclusion of Phase 1 of the feasibility assessment, the 18 feasible EEMs proceeded to Phase 2 of the structured approach. Phase 2 of the structured approach prioritises the feasible EEMs as discussed in the following section.

3.3.2 Phase 2: Prioritisation

Selection of prioritisation criteria

Phase 2 of the structured approach prioritises the projects that are deemed feasible by Phase 1. The suggested prioritisation criteria depicted in Figure 2-29 were modified according to the availability of information on the specific criteria.

Most of the *Technical* criteria information was available and only the *Achievable EE* and *Remaining lifetime of equipment* technical criteria from Figure 2-29 were not included in the technical prioritisation criteria for this case study. Unfortunately, very little information on the *Financial* criteria was available for the case study. Therefore, only *PP*, *Implementation cost*, *Cost savings*, and *Incentives* were chosen for the financial prioritisation criteria.

Since few of the possible *Financial* criteria were chosen due to limited availability of information, the *Financial* criteria were not categorised according to group. Figure 3-17 shows the chosen prioritisation criteria structured into a hierarchy. The hierarchy presented in Figure 3-17 was used for the weighting of the criteria according to the AHP process described in Section 2.5.

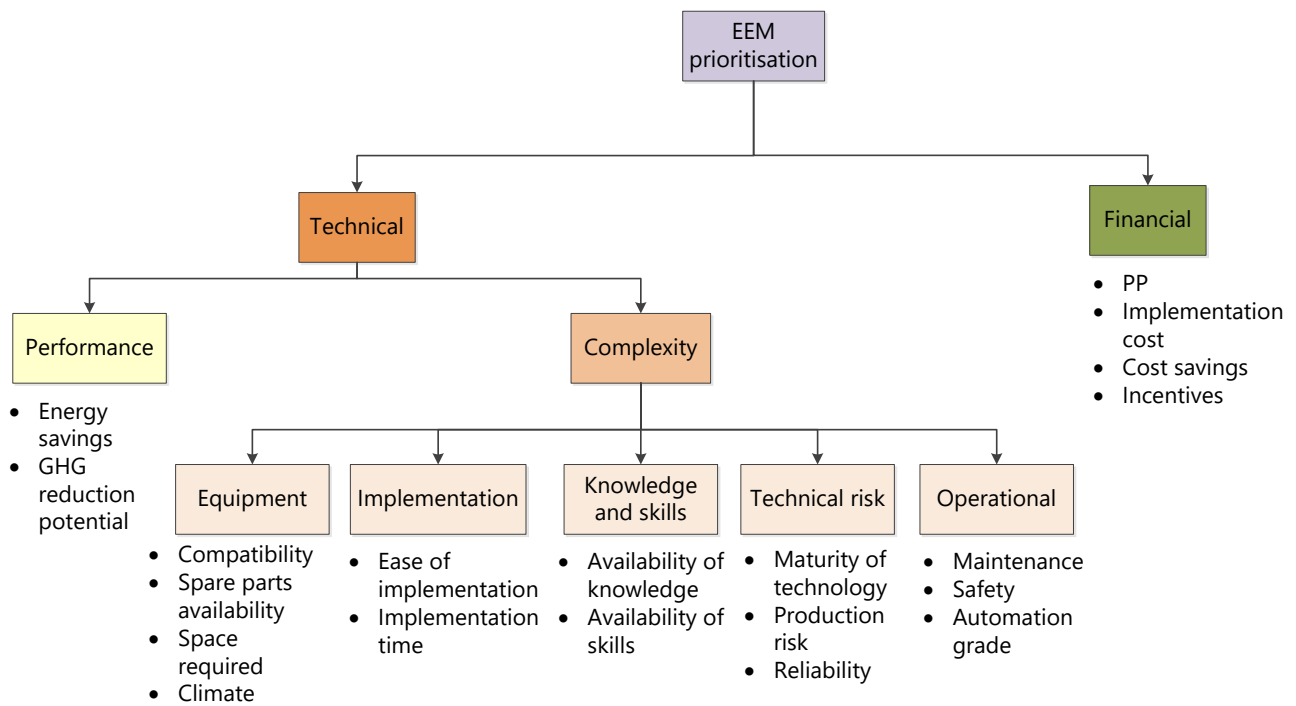


Figure 3-17: The prioritisation criteria chosen for the case study (adapted from Figure 2-29).

Weighting of the prioritisation criteria

To weight the prioritisation criteria, pair-wise comparisons were made via questionnaire by individuals with energy management experience. Since information on all of the proposed prioritisation criteria are not available, the questionnaire provided in Appendix D.1 was modified according to the available criteria information. The adapted questionnaire is provided in Appendix F.2. The weighting of the prioritisation criteria by the 22 respondents was accomplished by completing Table F-4 to Table F-14 of Appendix F.2.

To ensure anonymity, the questionnaire responses were aggregated according to the *aggregation of individual judgements* (AIJ) procedure described in Section 2.6.2. The aggregated judgement matrices for the complexity criteria are shown in Table G-1 to Table G-6 of Appendix G. The aggregated judgement matrices for the remainder of the prioritisation criteria are shown in Table H-1 to Table H-4 of Appendix H.

The global weights of the high-level criteria were calculated from the aggregated judgement matrices and are shown in Figure 3-18. Figure 3-18 shows that the questionnaire respondents regard the *Financial* criteria category as significantly more important than the *Technical* criteria category. This finding is validated by the literature review in Section 1.3 where all the consulted literature

sources of Table 1-2 conducted a financial analysis, but only a third of the studies considered the technical feasibility of EEMs.

Therefore, the *Financial* criteria are considered significantly more important by the literature as well as by the respondents of the questionnaire. The *Technical* criteria of EEMs may therefore be unwisely neglected during project prioritisation since emphasis is placed on the financial criteria.

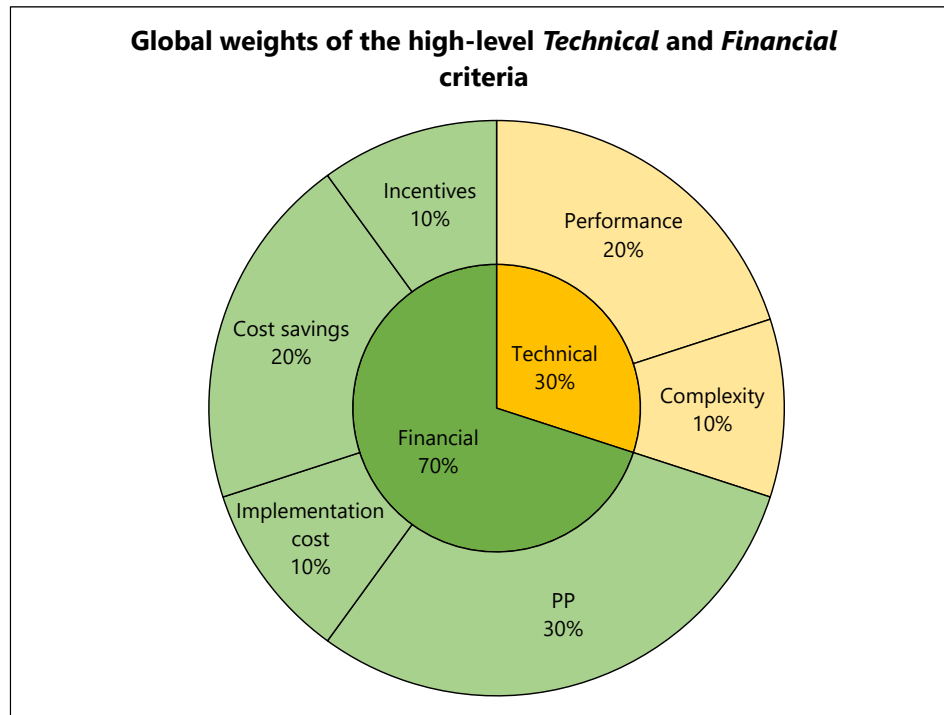


Figure 3-18: The global weights of the high-level criteria obtained from the questionnaire.

Figure 3-18 furthermore shows that the *PP* was regarded as the most important financial prioritisation criterion. *Cost savings* was regarded as the second most important criterion followed by the *Implementation cost*. *Incentives* were regarded as the least important financial criterion. These findings are validated by the literature review of financial prioritisation criteria in Section 2.3.2 where *Implementation cost*, *PP*, and *Cost savings* were rated as the top three criteria and *Incentives* was rated significantly lower at 9th place.

However, the benefits of utilising incentives were clearly illustrated in Section 3.3.1. The Stage 3 results of the case study showed that 5% of the total energy savings and 7% of the total cost savings would have been disregarded if incentives were not considered. Furthermore, the estimated incentive benefits for the qualifying EEMs amount to the cost savings and half of the implementation cost of the qualifying EEMs. It is therefore concluded that despite the findings from literature and the

questionnaire responses, *Incentives* are valuable to the feasibility assessment and prioritisation of EEMs.

From Figure 3-18, it is observed that the *Performance* criterion of the *Technical* criteria category contributes a fifth (20%) of the total prioritisation weight of all the criteria. This observation is validated by the literature review of *Technical* criteria in Section 2.3.1. The literature review showed that *Energy savings* and *Greenhouse gas (GHG) reduction potential*, which comprise the *Performance* category, were regarded as the two most important *Technical* criteria.

Finally, Figure 3-18 indicates that all the criteria comprising the *Complexity* category only contribute to 7% of the total prioritisation weight. This finding is validated by the literature review in Section 2.3.1 where Figure 2-2 showed that the *Complexity* criteria were significantly less referenced than the *Performance* criteria.

Figure 3-19 shows the global weights of the *Technical* criteria that were obtained from the questionnaire. Figure 3-19 shows that the *Energy savings* and *GHG reduction potential* were assigned similar global weights, with a 10% contribution to the overall prioritisation. This is validated by the literature review in Section 2.3.1 where the *Energy savings* and *GHG reduction potential* were the two most referenced criteria. Figure 3-19, as well as the analysis conducted on the *Complexity* criteria groups in Section 3.3, corroborate the literature findings of Section 2.3.1 that the *Technical risk* category is the most important *Complexity* category.

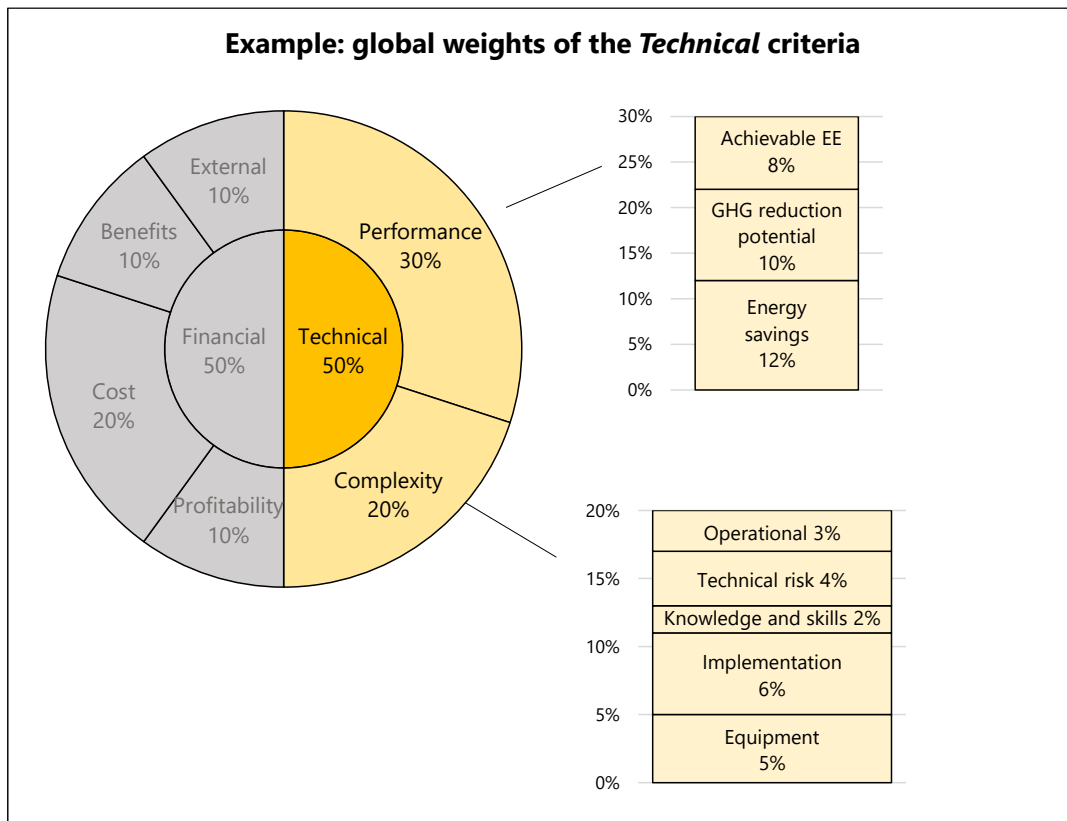


Figure 3-19: The global weights of the *Technical* criteria obtained from the questionnaire.

Figure 3-20 shows the global weights of the individual criteria comprising the *Complexity* category. Figure 3-20 show that *Production risk* and *Safety* are regarded as the most important *Complexity* criteria since both criteria were weighted significantly heavier than the other *Complexity* criteria. A detailed discussion on the individual *Complexity* criteria weights assigned by the questionnaire respondents was provided in Section 3.3.1 as part of the results discussion of Stage 2 of the feasibility assessment.

Figure 3-21 shows the global criteria weights of the prioritisation criteria on each of the lowest levels of the hierarchy. Figure 3-21 emphasises that the *Financial* criteria are considered the most important criteria overall, with the *PP* alone contributing 30% to the overall prioritisation. The *Performance* category, comprising of *Energy savings* and *GHG reduction potential*, contribute roughly 20% of the overall prioritisation score. Figure 3-21 shows that the *Complexity* criteria contribute little to the overall prioritisation compared to the aforementioned criteria.

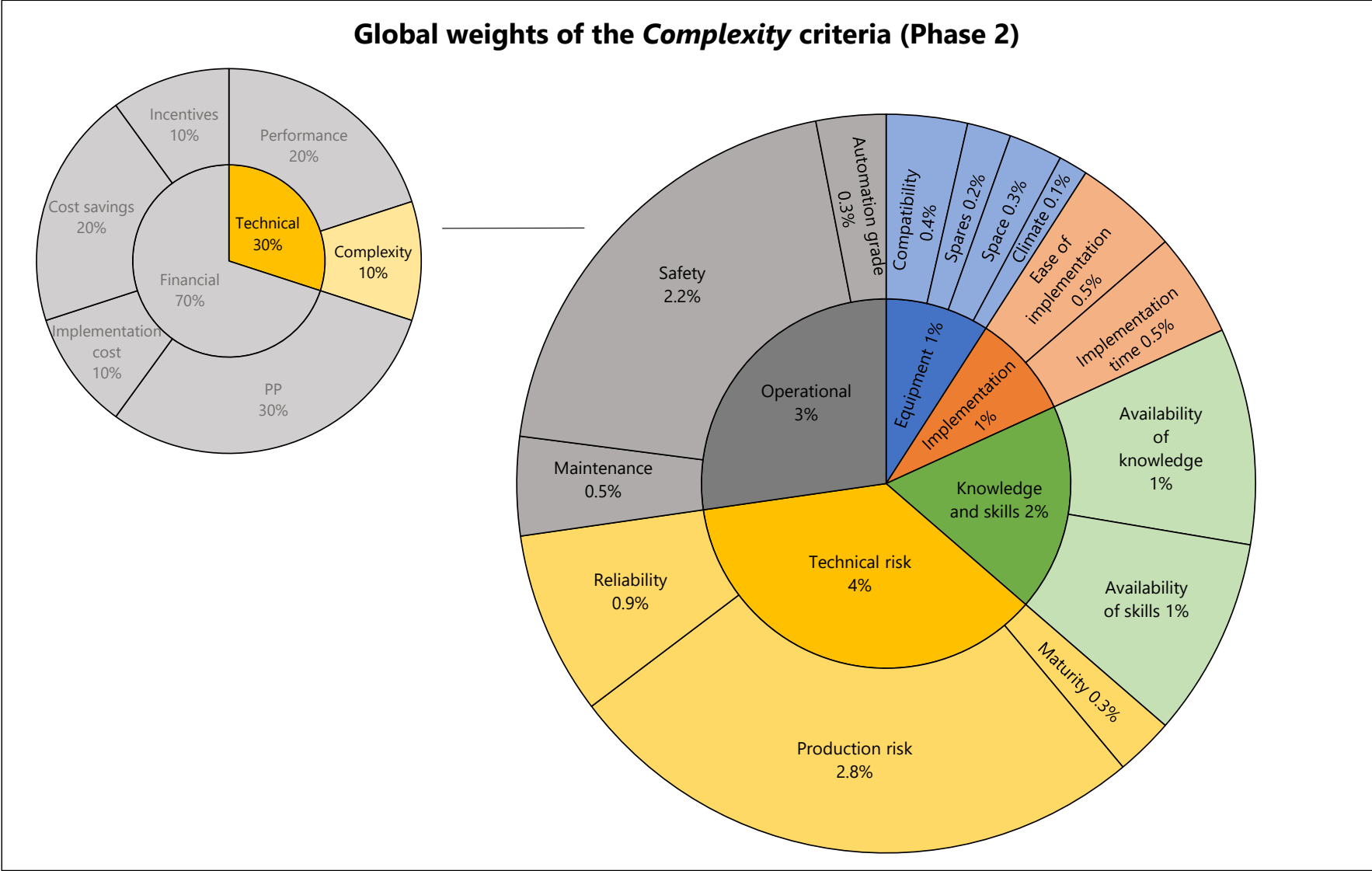


Figure 3-20: The global weights of the *Complexity* criteria obtained from the questionnaire.

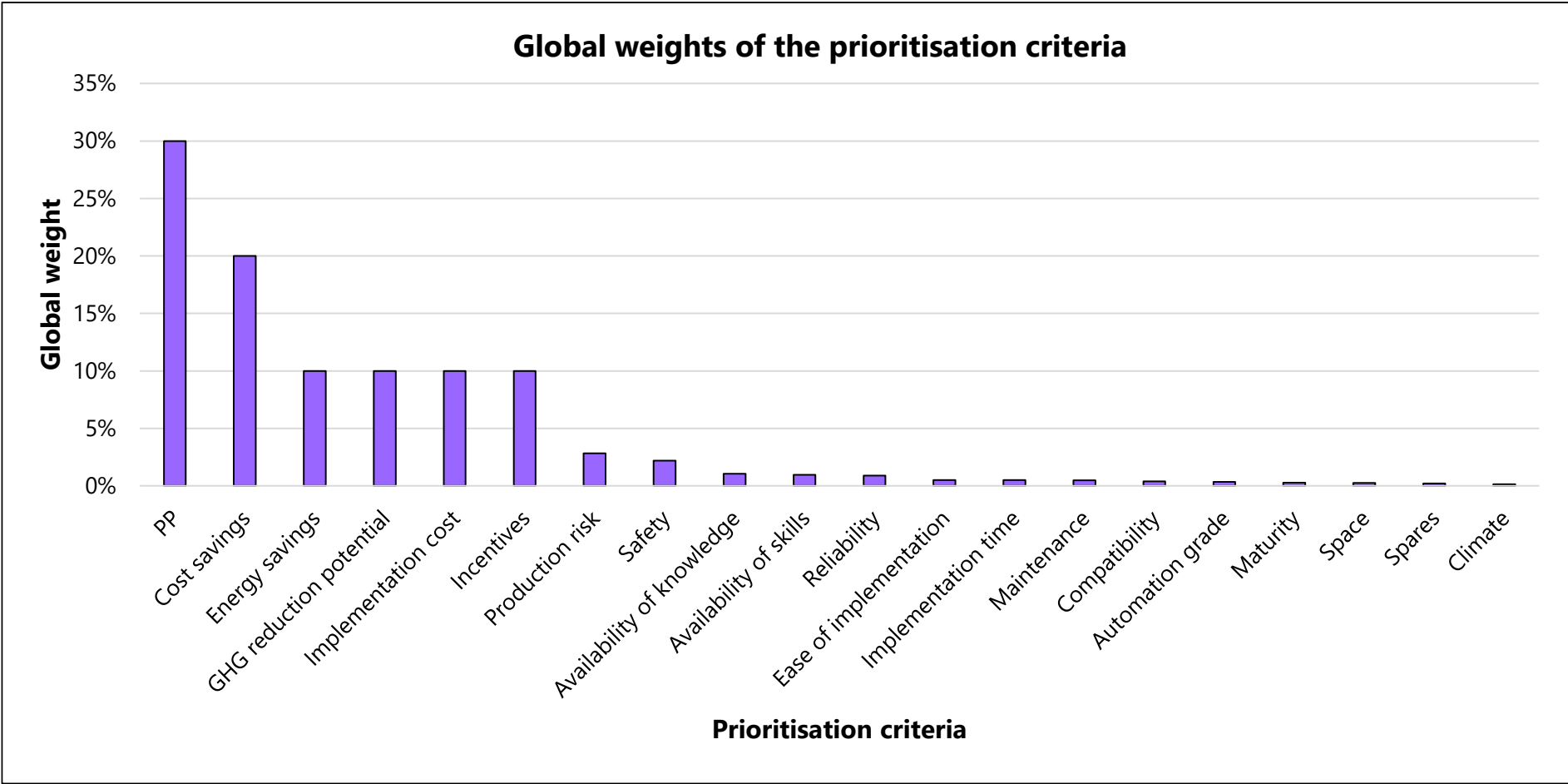


Figure 3-21: The global weights of the prioritisation criteria obtained from the questionnaire.

Final prioritisation scores

After the calculation of the global weights of the prioritisation criteria, the EEMs that proceeded to Phase 2 of the structured approach are evaluated. A rating was assigned to each EEM with respect to each criterion. For the qualitative prioritisation criteria, the ratings model from Table 2-9 was used to assign scores to each EEM. For the quantitative prioritisation criteria, the numerical value of the EEM with respect to the criterion was used as its rating.

The local weight of each EEM with respect to each criterion was calculated by normalisation as described in Step 3 of Section 2.5. After the assignment of local weights to each of the EEMs, the final prioritisation score of each EEM was calculated using Equation (8) in Section 2.5. The implementation order of the EEMs was subsequently ranked according to the final prioritisation scores as shown in Figure 3-22. The normalised prioritisation scores assigned to each EEM for each prioritisation criterion as well as the final overall prioritisation score for each EEM are available in Table H-5 in Appendix H.2.

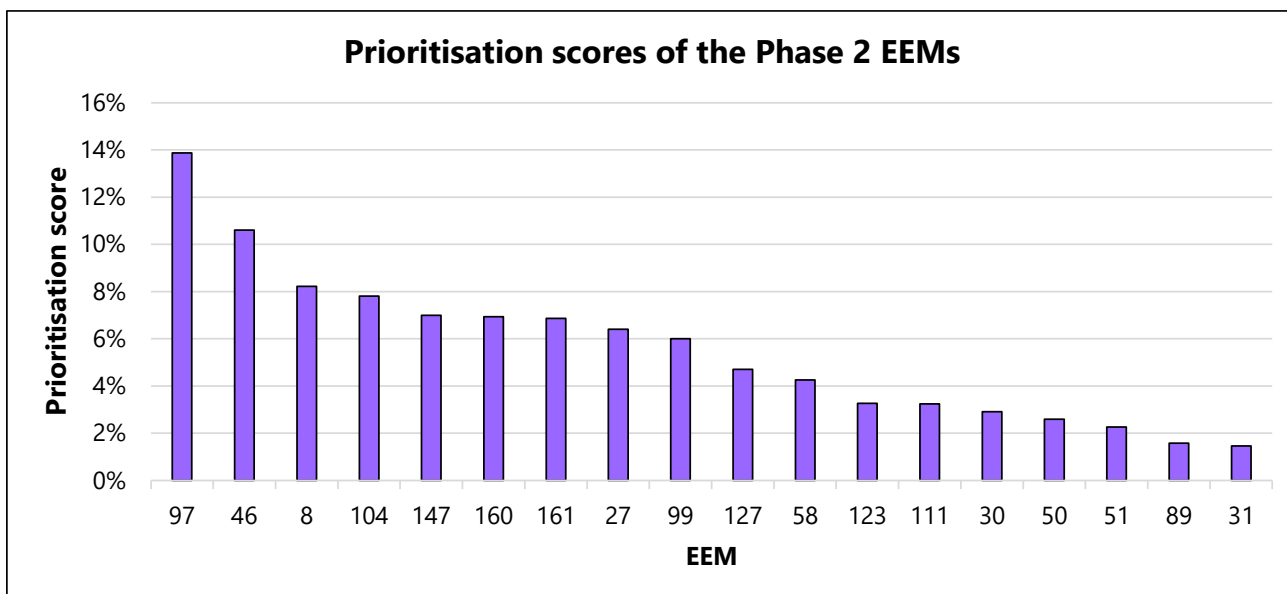


Figure 3-22: The prioritised Phase 2 EEMs of the case study.

Figure 3-22 shows that EEM 97 had the highest prioritisation score, contributing 14% to the goal of EE. EEM 31 has the lowest prioritisation score, contributing less than 2% to the goal. It is evident from the prioritisation scores shown in Figure 3-22 that no single EEM will achieve the goal of EE alone. However, implementation of the five EEMs with the highest prioritisation scores will contribute nearly 50% to the total potential EE. Significant progress towards EE can therefore be achieved by implementing the top five EEMs.

The results from applying the developed approach recommend that the EEMs are implemented in the order shown in Figure 3-22. An EEM with a higher prioritisation score should be implemented before an EEM with a lower score. Thus, EEM 97 should be implemented first and EEM 31 should be implemented last. If all 18 feasible EEMs are implemented, energy savings of 1.3 TWh, cost savings of R332 million and incentive shareholder value of R338 million are estimated.

The implementation of the EEMs on the prioritised list will contribute to the achievement of the facility's EE target.

Phase 2 conclusion

Prioritisation criteria were selected for the case study based on the availability of information. The prioritisation criteria were weighted by aggregating the questionnaire responses of 22 individuals with energy management experience. Ratings were assigned to each feasible EEM with respect to each prioritisation criterion. The final prioritisation score for each EEM was calculated and the implementation order of the feasible EEMs was proposed.

Energy savings of 1.3 TWh per annum, cost savings of R332 million, and incentive shareholder value of R338 million are estimated if all the measures on the prioritised list are implemented.

3.3.3 Summary of the case study results

Figure 3-23 provides a summary of the case study results. 18 of the initial 161 EEMs were deemed feasible by Stage 1 of the structured approach. The feasible EEMs were prioritised by using criteria weighted by individuals with energy management experience.

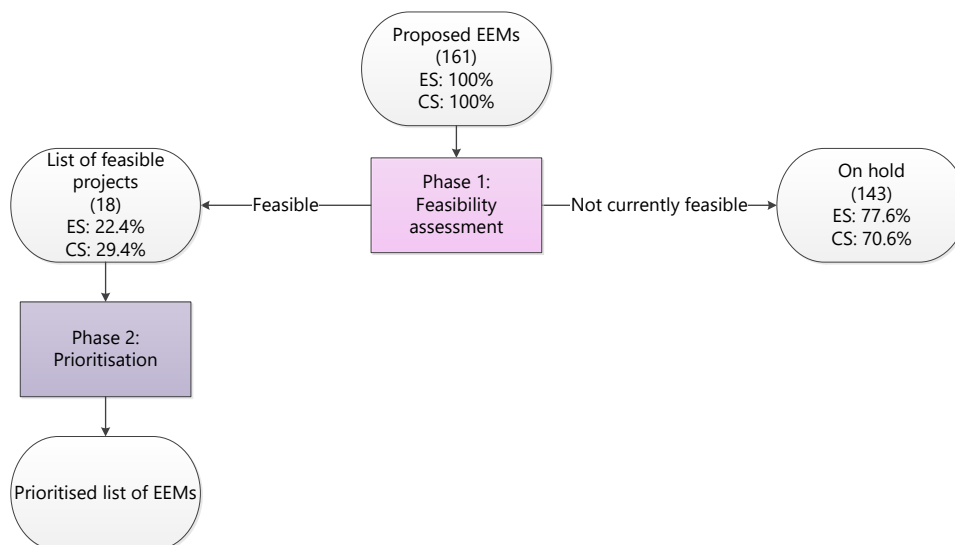


Figure 3-23: A summary of the case study results.

3.4 Validation of the structured approach

The previous section discussed the implementation of the developed approach on the case study facility. The results show that the method can be used on a real-world facility to generate the intended feasibility and prioritisation results. This section focusses on the relevance cycle of the DSR methodology by evaluating whether the approach solves the identified problem statement.

Figure 3-24 shows that the validation discussion consists of three topics. The first validation method analyses the questionnaire responses. The second validation method involves the comparison of the implementation status of the EEMs of the case study with the prioritised list of EEMs from the structured approach. The outcomes from applying the structured approach to the case study are compared to the problem statement as the third validation method.

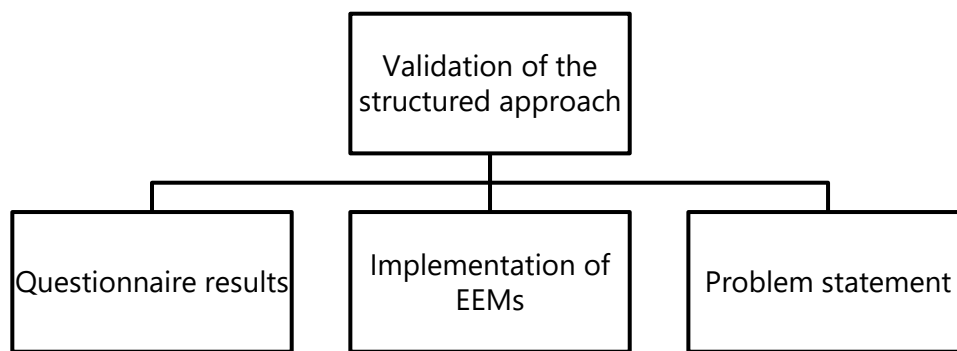


Figure 3-24: Validation methods for the structured approach and the case study results.

3.4.1 Questionnaire results

The first validation method involves a comparison of the questionnaire results to observations from literature. The discussion of the results in Section 3.3.2 found satisfactory agreement between the global weights assigned to the prioritisation criteria via questionnaire and the findings from the literature review in Section 2.3.

Figure 3-25 shows a comparison between the criteria identified from the literature review in Section 2.3 and the criteria weights obtained from the questionnaire. Figure 3-25 shows that the top five criteria from the literature review agree with the top five weighted criteria from the questionnaire. Therefore, the criteria used in the structured approach are validated by literature.

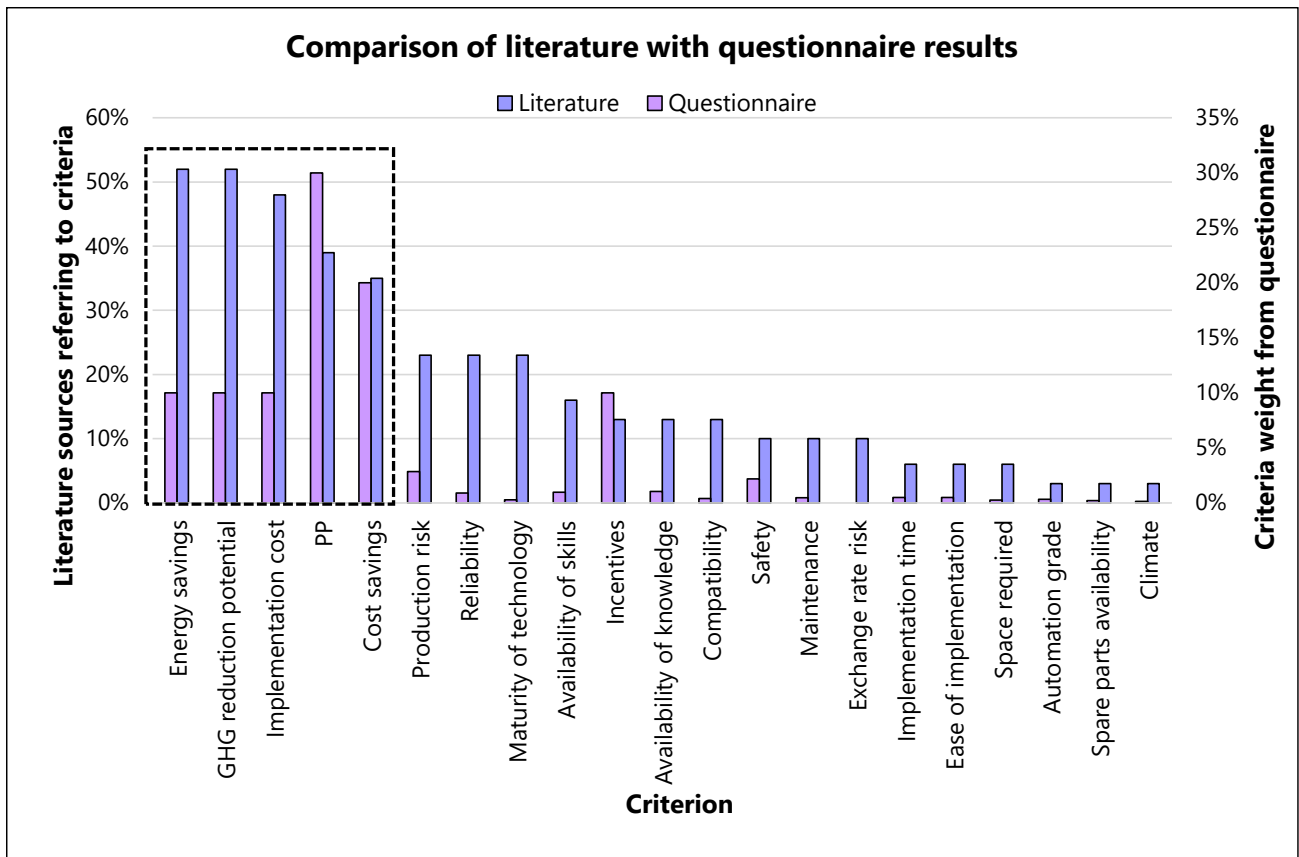


Figure 3-25: Comparison of the questionnaire criteria weights with literature findings.

The questionnaire provided opportunity for additional criteria recommendations. Of the 22 respondents, only three respondents recommended additional criteria. The additional criteria recommended are (1) buy-in from site personnel; (2) net present value (NPV) analysis over ten years; and (3) data quality and availability.

The few recommendations of additional criteria validate the comprehensiveness of the prioritisation criteria used in the structured approach. Furthermore, by weighting the prioritisation criteria, the questionnaire respondents inherently validated the prioritisation criteria used in the structured approach.

3.4.2 Implementation status of EEMs

The second validation method is the comparison of the actual project implementation to that of the prioritised list for the case study. Figure 3-26 shows that 9 of the 18 EEMs on the prioritised list were successfully implemented by the facility. The Section 12L tax incentive benefits amounting to R135 million in shareholder value have been claimed on 4 of the 9 implemented EEMs. Four (4) of the EEMs are planned for future implementation while 5 of the EEMs are not currently prioritised.

The successful implementation of half of the EEMs as well as the planned implementation of 22% of the EEMs on the prioritised list validate the structured approach.

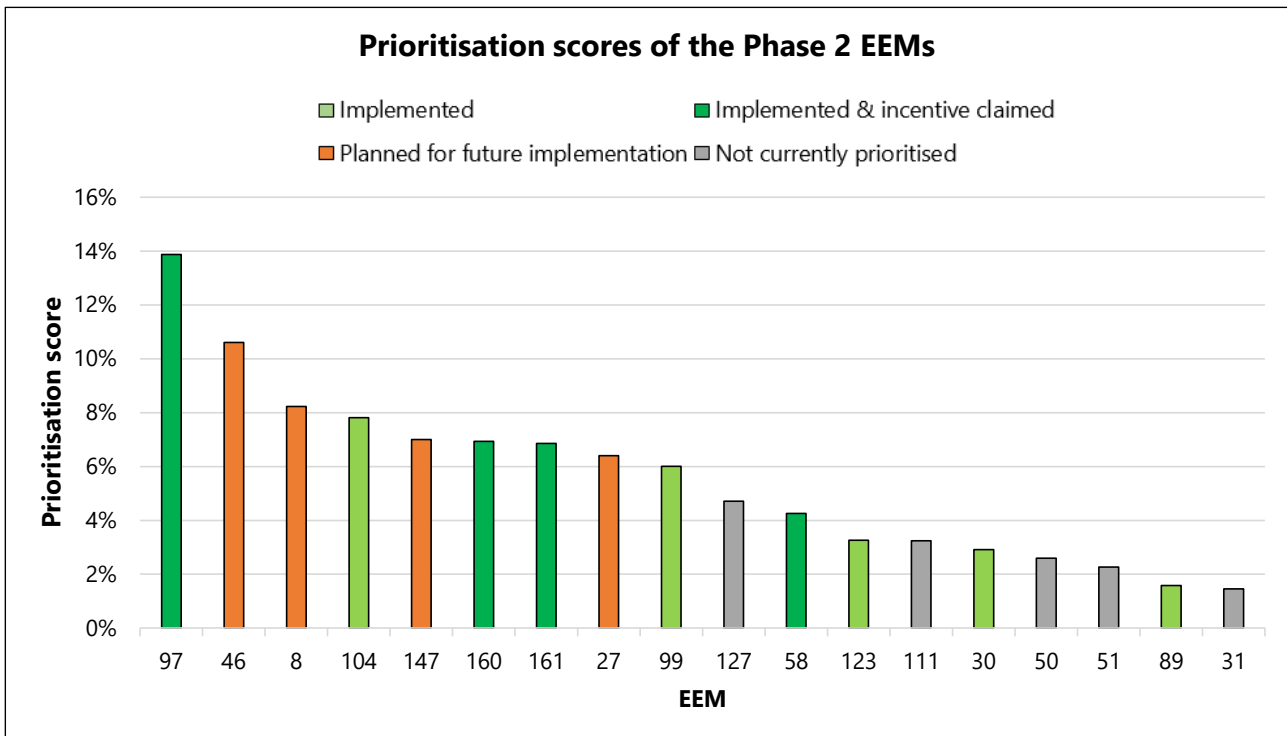


Figure 3-26: The prioritisation scores and implementation statuses of the case study EEMs.

The implementation status of all 161 initial EEMs was considered to evaluate the effectiveness of the structured approach. 10 additional EEMs that were placed “On hold” by Phase 1 of the approach have in reality been successfully implemented by the facility.

All 10 EEMs were discounted in the screening phase (Stage 1) of the feasibility assessment. Two (2) of the 10 EEMs were placed on hold due to a lack of background information. Five (5) EEMs were placed on hold due to unavailable energy savings estimates. The remaining 3 EEMs were placed on hold due to the unavailability of a PP.

A lack of general project information led to the oversight of the 10 EEMs that were in fact successfully implemented. This phenomenon demonstrates the importance of the availability of project information in feasibility assessment and ultimately project prioritisation.

3.4.3 Problem statement verification

The last validation method was the comparison of the case study results to the problem statement stated in Section 1.4. The problem statement states that the three most prevalent barrier themes

identified from literature are not adequately addressed. The three most prevalent barrier themes are a shortage of financial resources, project uncertainty, and limited time and human resources.

The detailed incentive analysis from the case study estimated that the successful utilisation of the Section 12L tax incentive may yield incentive benefits that amount to the cost savings and nearly half of the total implementation cost for the qualifying measures. It is evident that the case study results validate that the utilisation of incentives as part of the structured approach addresses the shortage of financial resources barrier theme.

The case study results of Phase 1 showed that the designed approach evaluated the feasibility of EEMs in a structured and systematic manner through three stages of feasibility assessments. The case study results show that the feasibility assessment resulted in a list of feasible EEMs. The results therefore validate that the structured approach addresses the project uncertainty barrier theme, since the technical and financial feasibility status of each EEM is known after applying Phase 1 of the approach.

Figure 3-27 shows a summary of the results of the feasibility assessment of Phase 1. Figure 3-27 highlights that a significant amount of time can be wasted on pursuing EEMs that are not currently feasible. The feasibility of multiple available EEMs is systematically evaluated via three stages that progress in detail and time required for evaluation. Thus, a substantial amount of time may be saved by assessing the feasibility of EEMs using the structured approach. This addresses the limited time and human resources barrier theme.

Furthermore, applying Phase 2 of the structured approach resulted in a prioritised list of EEMs and a recommended implementation order of the feasible EEMs. The feasible, prioritised list of EEMs for the case study validate that the structured approach addresses the limited time and human resources barrier theme by identifying the EEMs for implementation that justify the use of the facility's limited resources.

From the discussion of the three validation methods shown in Figure 3-24, it is concluded that the designed structured approach is validated. The validation proves that the design process is linked to the research environment via the relevance cycle of the DSR methodology.

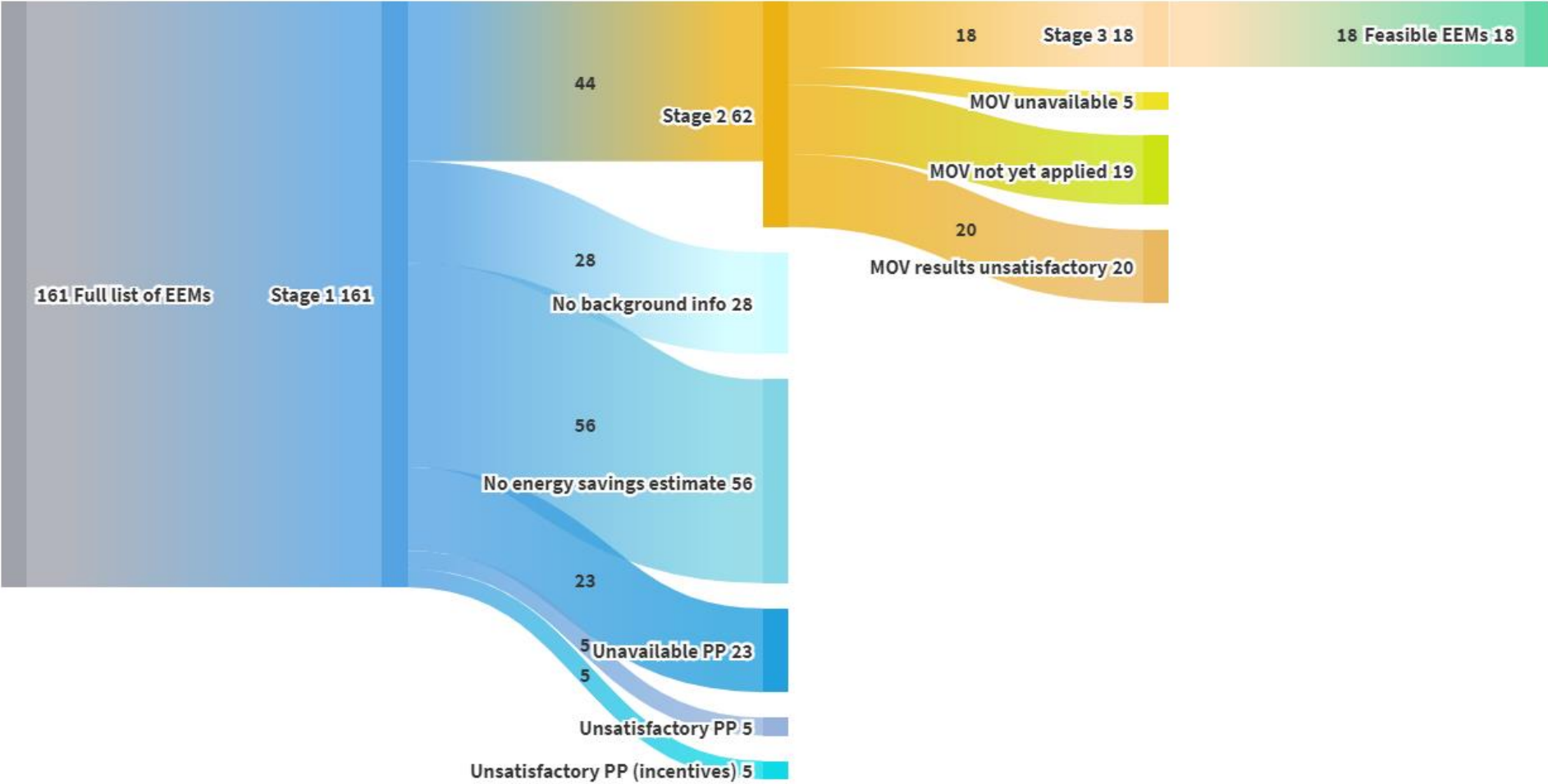


Figure 3-27: A summary of the results of Phase 1.

3.5 Conclusion

The structured approach designed in Section 2.6 was validated by applying it to a case study. A large industrial facility with 161 proposed EEMs was chosen as the case study. Phase 1 of the structured approach evaluated the feasibility of the proposed measures through three stages of assessments.

By using rough estimations of possible incentive benefits, Stage 1 of the feasibility assessment was an effective screening of the proposed EEMs, with 117 EEMs placed on hold. Stage 2 assigned complexity levels to the remaining EEMs in order to evaluate the technical feasibility of the EEMs. The value of using incentives as part of the feasibility assessment was demonstrated during the financial feasibility assessment of Stage 3. Ultimately, 18 of the proposed EEMs passed through all three stages of feasibility assessments and were thus deemed feasible.

Phase 2 of the structured approach prioritised the feasible EEMs by using weighted criteria. The prioritisation criteria were weighted by 22 individuals with energy management experience. A final prioritisation score was assigned to each EEM using normalisation of the assigned ratings and the global weights of the prioritisation criteria.

The structured approach was validated using three methods. The questionnaire results showed agreement with the findings from the literature review. Only three questionnaire respondents suggested additional criteria. Therefore, the chosen prioritisation criteria used in the structured approach are validated.

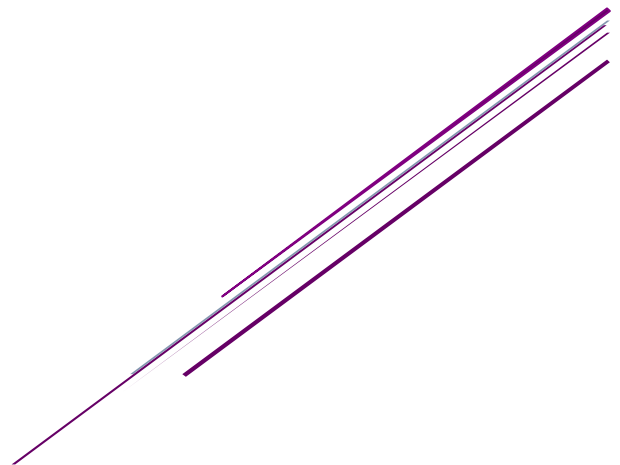
The second validation method was a comparison between the implementation status of the case study EEMs to the prioritised list. 50% of the EEMs have been successfully implemented of which 22% had successful Section 12L applications. The successful implementation and incentive claims of these EEMs validate the structured approach and ultimately the results thereof.

The findings from the case study were used to evaluate the problem statement from Section 1.4. The case study results act as validation since the three barrier themes identified in the problem statement are addressed by the structured approach.

CHAPTER 4:

CONCLUSION AND

RECOMMENDATIONS



4 CONCLUSION AND RECOMMENDATIONS

4.1 Preamble

Chapter 4 serves as a conclusion to the study by summarising the main findings of the dissertation.

Figure 4-1 shows a summary of the contents of Chapter 4.

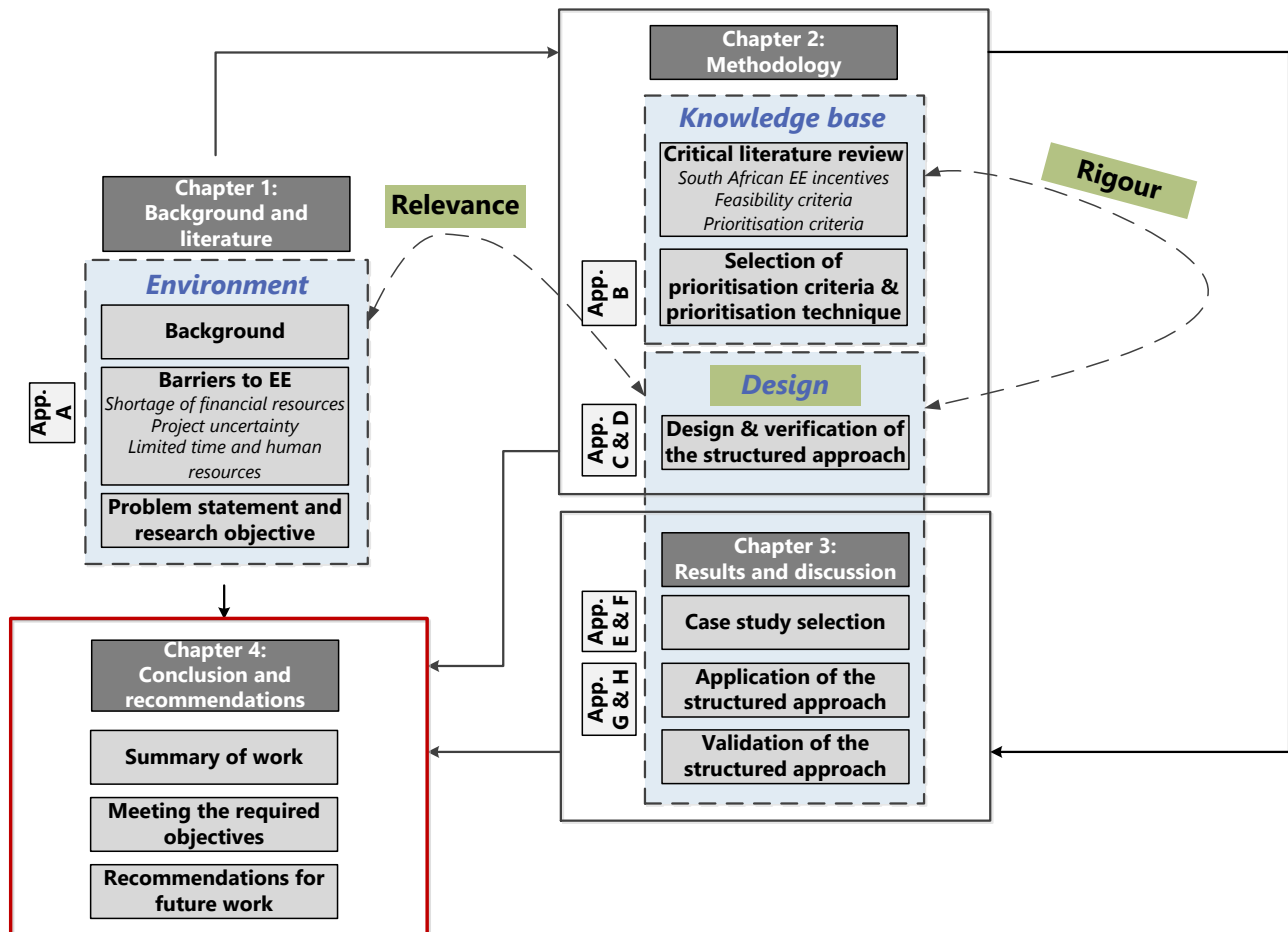


Figure 4-1: The structure of Chapter 4 within the research methodology.

A summary of the dissertation is provided in Section 4.2. Section 4.3 contains a discussion of how the research objective was addressed. Recommendations for future work are provided in Section 4.4 and the document is concluded in Section 4.5.

4.2 Summary of work

Chapter 1: Introduction and literature

Chapter 1 highlighted the importance of energy efficiency (EE) by discussing various issues related to the growing global energy demand. The potential for industrial EE was illustrated by considering the extent of energy usage in industry, ambitious industrial EE targets, and a discussion of the multiple energy efficiency measures (EEMs) that can be implemented in industry.

Despite the potential for industrial EE, various barriers to EE were identified and discussed. Three prevalent industrial EE barriers were identified, namely a shortage of financial resources; project uncertainty; and limited time and human resources. Literature showed that utilising incentives, conducting feasibility studies, and prioritising multiple EEMs are mitigative strategies to address the three EE barriers.

A critical literature review was conducted to determine whether the three barriers are adequately addressed by the implementation of the proposed mitigative strategies. The literature review showed that all three EE barriers were rarely addressed concurrently. A need was therefore identified for a structured approach that systematically addresses all three barriers by utilising the mitigation measures identified from literature.

Consequently, the research objective requires that the structured approach utilises incentives, assesses the technical and financial feasibility of EEMs, and prioritises multiple EEMs.

Chapter 1 provides context on the research environment and links to Chapter 2 via the relevance cycle of the Design Science Research (DSR) methodology.

Chapter 2: Methodology

To meet the requirements of the research objective, a review of available incentives, various feasibility criteria, prioritisation criteria, and prioritisation techniques was conducted in Chapter 2. Various technical and financial feasibility criteria were compiled from literature, categorised, and validated for use as the prioritisation criteria. The Analytical Hierarchy Process (AHP) was chosen as the multi-criteria decision-making (MCDM) prioritisation technique. The structured approach was designed by dividing the approach into two phases. Phase 1 conducts a feasibility assessment and Phase 2 prioritises the feasible EEMs.

Phase 1 of the structured approach consists of three stages of feasibility assessment. Stage 1 is used to screen the multitude of possible EEMs based on the available technical project information as well as the high-level projected financial performance of the EEM. Estimations of possible incentive value are used to prevent the premature exclusion of EEMs with payback periods (PPs) higher than the maximum PP. Stage 2 determines the complexity level of the proposed EEMs and evaluates the technical feasibility thereof. Stage 3 involves a financial feasibility assessment and comprehensive incentive evaluations. The EEMs that pass through all three stages of Phase 1 proceed to Phase 2 for prioritisation.

Phase 2 of the structured approach involves the weighting of prioritisation criteria by energy management experts via questionnaire using the AHP method. The questionnaire responses are aggregated to determine the final global weights of the prioritisation criteria. Ratings are assigned to the EEMs with respect to each criterion and normalised.

The final prioritisation score for each EEM is calculated by adding the product of each normalised criterion score and the respective global weight of the criterion. The implementation order of the feasible EEMs is ranked according to the final prioritisation scores. The structured approach was verified by means of a checklist of the requirements of the research objective.

Chapter 2 represents the rigour cycle of the DSR methodology by utilising existing knowledge from literature to design the structured approach. Chapter 2 further encompasses the design cycle of the DSR methodology through the development of the structured approach.

Chapter 3: Results and discussion

The structured approach was validated in Chapter 3 by application to a case study. The case study is an industrial facility with 161 proposed EEMs. By applying Phase 1 of the structured approach, the initial list of proposed EEMs was filtered to 18 feasible EEMs. Phase 2 of the structured approach was applied by the weighting of the chosen prioritisation criteria by 22 individuals with energy management experience. The questionnaire responses were aggregated to determine the global weights of the prioritisation criteria. Ratings were assigned to the EEMs with respect to each criterion and the feasible list of EEMs was subsequently prioritised.

The structured approach was validated using three methods. A strong correlation was found between the global weights assigned to the prioritisation criteria via questionnaire and the findings from the

criteria literature review in Chapter 2. This acts as validation of the prioritisation criteria used in the structured approach.

For the second validation method, the prioritised list of feasible EEMs was compared to the actual implementation status of the EEMs. Nine (9) of the EEMs on the prioritised list have been successfully implemented. Section 12L incentives amounting to R135 million in shareholder value have been successfully claimed on 4 of the implemented EEMs. The final validation method showed how the results from the case study address the problem statement identified in Chapter 1.

Chapter 3 is included in both the design cycle and relevance cycle of the DSR methodology.

4.3 Meeting the required objectives

The literature review of Chapter 1 showed that there is a need for a structured approach that systematically addresses the three prevalent EE barriers by utilising the mitigation measures identified from literature. The structured approach needs to utilise incentives to address the shortage of financial resources that companies may face. The financial and technical feasibility of EEMs should be evaluated by the structured approach to address project uncertainty. Furthermore, to address the limited time and human resources of companies, the approach should use multiple criteria to prioritise the projects that are deemed feasible.

Therefore, the research objective of this study is to develop a structured approach to prioritise industrial EEMs that meet the following requirements:

1. The approach considers available financial incentives as part of the analysis of EEMs.
2. The approach systematically determines the technical and financial feasibility of EEMs.
3. The approach uses multiple criteria to prioritise the order in which the feasible projects should be implemented.

The following sections prove that each requirement of the research objective was met.

The approach considers available financial incentives as part of the analysis of EEMs

The available financial incentives are considered in both phases of the structured approach. In Phase 1, incentives are considered in both Stage 1 and Stage 3 of the feasibility assessment. During Stage 1, a rough estimation of the possible incentive value is used to prevent the premature abandonment of EEMs that may have acceptable PPs if incentive benefits are included. Stage 3

consists of a detailed incentive assessment to determine the possible incentive benefit for all the Stage 3 EEMs.

During Phase 2 of the structured approach, the incentive monetary value is used as a weighted prioritisation criterion. It is evident that the structured approach adequately addresses financial incentives since incentives are utilised by both phases of the approach.

The approach systematically determines the technical and financial feasibility of EEMs

Phase 1 of the structured approach consists of a systematic feasibility assessment via three stages. The first stage of the feasibility assessment considers the high-level feasibility of EEMs using both technical and financial criteria. The technical criteria considered in Stage 1 consist of an assessment of the availability of technical background information as well as estimations of the energy savings. The financial criteria are considered in Stage 1 through the screening of the PPs of the EEMs as well as estimations of the incentive value.

Stage 2 of the structured approach systematically determines the technical feasibility of the EEMs. First, a complexity level is assigned to each EEM. Minimum technical verification methods for each complexity level were proposed. Based on the assigned complexity level, the technical feasibility of the EEMs is evaluated by considering whether a satisfactory verification method is available, whether the verification method has been applied, and whether the results of the verification method are satisfactory.

Stage 3 of the structured approach consists of a systematic assessment of the financial feasibility of the EEMs. The EEMs are evaluated for possible incentives and the potential incentive benefit is calculated if there is a high level of certainty that the requirements of the incentive are met. The PP, including the incentive benefit, is calculated to assess the financial feasibility of the EEMs.

The three stages of feasibility assessment comprising Phase 1 of the structured approach are used to systematically determine the technical and financial feasibility of EEMs.

The approach uses multiple criteria to prioritise the order in which the feasible projects should be implemented

Phase 2 of the structured approach prioritises EEMs based on multiple technical and financial prioritisation criteria. A total of 18 technical criteria and 15 financial criteria were proposed as part of Phase 2. The approach therefore satisfactorily utilises multiple criteria to prioritise the EEMs.

The structured approach meets all three requirements of the research objective and is therefore validated as a solution to address the barriers related to a shortage of financial resources, project uncertainty, and a lack of time and human resources.

4.4 Recommendations for future work

Recommendations for extensions of the structured approach that may contribute to the research environment are listed below.

A comprehensive financial feasibility assessment

The emphasis of the designed approach was not placed on a comprehensive financial feasibility analysis, but rather on a high-level assessment thereof by assessing the PP. This was done due to the frequent unavailability of detailed financial analyses, such as net present value (NPV) assessments.

Section 1.3 showed that the financial feasibility of EEMs is widely considered during the evaluation of multiple EEMs. The structured approach can thus be further developed to include a detailed financial feasibility analysis for the consideration of EEMs with detailed financial information available.

A comprehensive incentive assessment

The structured approach utilises incentives as part of both the feasibility assessment and the prioritisation phases. Detailed reviews of available incentives and their requirements are excluded from the scope of this study since the incentive landscape is constantly evolving.

The structured approach can be extended by the detailed consideration of available incentives and a decision framework to determine what incentives to utilise. The specific requirements of the incentives can be reviewed in detail to improve the confidence of successful applications.

4.5 Closure

The most prevalent barriers to industrial EE were found to be a shortage of financial resources, project uncertainty, and limited time and human resources. Literature failed to provide a method that addresses all three barriers simultaneously. It is evident that there is a need for a clear and structured approach to determine the technical and financial feasibility of multiple EEMs before the EEMs can be prioritised via MCDM. Additionally, the need to include EE incentives in the structured approach was identified.

The structured approach was developed by reviewing and compiling various technical and financial feasibility criteria. The feasibility criteria were validated for use as the prioritisation criteria. The AHP method was chosen as the prioritisation method. The structured approach consists of two phases. Phase 1 of the structured approach systematically determines the feasibility of EEMs through three stages of feasibility assessments that include the consideration of incentives. Phase 2 of the approach prioritises the EEMs based on prioritisation criteria that are weighted by energy management experts via questionnaire.

The case study proved the efficacy of the structured approach by filtering 161 proposed EEMs to a prioritised list of 18 feasible EEMs. Energy savings of 1.3 TWh, cost savings of R332 million, and incentive shareholder value of R338 million are estimated if all the measures on the prioritised list are implemented.

The case study highlighted the value of considering incentives as part of the feasibility assessment, since the calculated monetary incentive value for the qualifying EEMs amounts to the cost savings and nearly half of the implementation cost of the qualifying incentives. Half of the EEMs on the prioritised list have been implemented to date, and incentives amounting to R135 million in shareholder value have been claimed through the Section 12L tax incentive.

The structured approach provides a systematic approach to determine the feasibility of EEMs by utilising incentives. Furthermore, the approach prioritises EEMs using multiple criteria. Therefore, the structured approach satisfactorily addresses the prevalent EE barriers of a shortage of financial resources, project uncertainty, and a lack of time and human resources.

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A. APPENDIX A: Barriers to energy efficiency (Chapter 1)

This appendix includes supplementary information on the first chapter of the study. Chapter 1 contained a review of various studies that evaluate barriers to industrial energy efficiency (EE). Appendix A.1 summarises the studies that were considered and categorises the most prevalent barriers to EE of each study.

Appendix A.1

- A categorisation of the barriers to EE identified from literature (Section 1.2.3).

Appendix A.1: Categorisation of barriers to energy efficiency

Various studies that evaluate barriers to industrial EE were reviewed in Chapter 1 to identify and categorise the most prevalent barriers to EE. Table A-1 provides a summary of the studies that were considered with the main barriers emphasised by each study and the associated barrier category.

Table A-1: A review and classification of the barriers to industrial energy efficiency.

Source	Main barriers	Barrier category
[31]	Technical risks	<i>Risk</i>
	Limited access to capital	<i>Access to capital</i>
	Other priorities for financial investment	<i>Access to capital</i>
[33]	Hidden costs	<i>Hidden costs</i>
	Access to capital	<i>Access to capital</i>
	Limited rationality	<i>Bounded rationality</i>
[34]	Other priorities for capital investment	<i>Access to capital</i>
	Hidden costs	<i>Hidden costs</i>
	Technical feasibility wasn't studied before	<i>Risk</i>
[35]	Investment costs too high	<i>Access to capital</i>
	Other investments have higher priority	<i>Other priorities for capital investment</i>
[36]	Hidden costs	<i>Hidden costs</i>
	Values	<i>Values</i>
	Risk	<i>Risk</i>
[41]	Other priorities for financial investment	<i>Access to capital</i>
	Technology not applicable to process	<i>Risk</i>
[42]	Other priorities for capital investment	<i>Access to capital</i>
	Lack of budget funding	<i>Access to capital</i>
	Access to capital	<i>Access to capital</i>
[43]	Lack of knowledge and awareness	<i>Lack of time and human resources; Imperfect information</i>
	High upfront costs	<i>Access to capital</i>
	High costs of financing	<i>Access to capital</i>
[44]	Slim organisation	<i>Lack of time and human resources</i>
	Lack of time/other priorities	<i>Lack of time and human resources</i>

Source	Main barriers	Barrier category
	Non-energy related working tasks are prioritised higher	<i>Lack of time and human resources</i>
	High complexity of production processes	<i>Risk</i>
	Lack of access to capital	<i>Access to capital</i>
[45]	Budget restrictions and investment priorities	<i>Access to capital</i>
	Rules of investment decision making	<i>Access to capital</i>
	Technology fitting in actual process	<i>Risk</i>
[46]	Access to capital	<i>Access to capital</i>
	Scarce information regarding energy efficiency opportunities and winning solutions	<i>Imperfect information</i>
	Poor information for the energy efficiency decisions	<i>Imperfect information</i>
[47]	Availability of appropriate infrastructure	<i>Risk</i>
	Utilisation of low-grade heat	<i>Risk</i>
	High capital costs	<i>Access to capital</i>
[48]	Lack of budget funding	<i>Access to capital</i>
	Other priorities for capital investment	<i>Access to capital</i>
	Lack of time or other priorities	<i>Lack of time and human resources</i>
[49]	Information issues on energy contracts	<i>Imperfect information</i>
	Lack of interest in energy efficiency interventions	<i>Company culture</i>
	Hidden costs	<i>Hidden costs</i>
[50]	Investment costs	<i>Access to capital</i>
	Information issues on energy contracts	<i>Imperfect information</i>
	Hidden costs	<i>Hidden costs</i>
[51]	Lack of budget funding	<i>Access to capital</i>
	Access to capital	<i>Access to capital</i>
	Other priorities for capital investment	<i>Access to capital</i>
[52]	Other investments are more important	<i>Access to capital</i>
	Investment cycle: new technology can only be implemented when existing technology is to be replaced	<i>Access to capital</i>
	Internal financial constraint	<i>Access to capital</i>
[53]	Technical risks	<i>Risk</i>

Source	Main barriers	Barrier category
	Strict adherence to capital budgets	<i>Access to capital</i>
	Energy manager lacks influence	<i>Power</i>
[54]	Lack of budget funding	<i>Access to capital</i>
	Information	<i>Imperfect information</i>
	Limited internal skills	<i>Lack of time and human resources</i>
[55]	Lack of time/other priorities	<i>Lack of time and human resources</i>
	Split incentives	<i>Split incentives</i>
	Incomplete information	<i>Incomplete information</i>
[56]	Limited time	<i>Lack of time and human resources</i>
	Information	<i>Imperfect information</i>
	Limited resources	<i>Lack of time and human resources</i>
[57]	Lack of time or other priorities	<i>Lack of time and human resources</i>
	Other priorities for capital investment	<i>Access to capital</i>
	Access to capital	<i>Access to capital</i>

B. APPENDIX B: Prioritisation (Chapter 2)

This appendix is divided into two sections that provide supplementary information on Section 2.5. Appendix B.1 contains a short summary of the available multi-criteria decision making (MCDM) prioritisation techniques. The Analytical Hierarchy Process (AHP) prioritisation method is explained and illustrated in detail in Appendix B.2.

Appendix B.1:

- A short summary of various MCDM prioritisation techniques is provided (Section 2.5)

Appendix B.2:

- A detailed explanation and illustration of the AHP (Section 2.5).

Appendix B.1: Summary of MCDM prioritisation techniques

Common MCDM prioritisation methods used in the energy field are listed in Section 2.5. A short description of each prioritisation method is provided in the following paragraphs. A detailed analysis of various MCDM methods with illustrative examples can be found in [100, 101].

The Weighted Sum Method (WSM) is the simplest MCDM method where the overall value of each alternative is equal to the total sum of the products [101]. The WSM is commonly used in single-dimensional problems where the units over the different criteria are the same. Difficulties arise in the utilisation of the WSM when criteria units differ such as in the case of qualitative and quantitative criteria [101].

The Weighted Product Method (WPM) is similar to the WSM with the product used in the method instead of the sum. The alternatives are compared to one another through the multiplication of ratios related to each criterion [101].

The AHP method deconstructs the decision-making problem into a hierarchical structure with the aim at the top of the hierarchy [101]. The subsequent levels include the various criteria that affect the decision. The alternatives are shown on the bottom level of the hierarchy. Pair-wise comparisons are used to assign weights to the various criteria. The AHP is widely used in the energy field due to its simplicity and the ability to check the consistency of the judgement matrices [101].

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method follows the philosophy that the optimal alternative is both closest in distance to the ideal solution and furthest from the least ideal solution [101]. Advantages of the TOPSIS method include its simplicity and its ability to maintain the same number of steps regardless of the problem size [100]. It is, however, difficult to weight the criteria and keep consistent judgements, especially when additional criteria are added [100].

The elimination et choix traduisant la réalité (ELECTRE) method has evolved through a number of versions that are all based on the same foundational concept of outranking based on concordance analysis [101]. The ELECTRE method consists of two main parts. The first part is the construction of one or more outranking relations to comprehensively compare each pair of actions [101, 122]. The second part is an exploitation procedure that elaborates on the recommendations of the first

phase [122]. The ELECTRE method is usually used to discard unwanted alternatives before the remaining alternatives are evaluated with another MCDM method.

The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) is an outranking method with several iterations available [100]. An independent preference function is used by the decision-maker to decide between two actions. The alternatives are then compared to one another with respect to the preference function. The results of the comparisons and the criteria values of each alternative are illustrated in a matrix. Partial ranking is then conducted after which a final ranking procedure is performed [101]. The PROMETHEE method does not require the assumption that criteria are proportionate; however, it does not provide a clear method for assigning criteria weights [100].

Appendix B.2: Illustration of the AHP method

A simplified explanation of the AHP method was provided in Section 2.5. This appendix provides a more in-depth explanation of the prioritisation method.

The application of AHP to a decision problem involves five steps [103]. The five steps are explained and illustrated in the subsections that follow.

Step 1: Hierarchical structuring of the decision problem

The first step is the structuring of the decision problem into a hierarchical model. Elements of the decision problem are grouped based on common characteristics and formulated into a hierarchy with different levels. A simple AHP model has three levels, namely the goal, the criteria and the alternatives [103].

The simple AHP model can, however, be adapted with more levels to accommodate more complex decision-making problems, such as the addition of subcriteria. The number of criteria that can be compared and judged simultaneously without error is 7 ± 2 [104]. Therefore, it is encouraged to group similar criteria so that the number of criteria per level in the hierarchy does not exceed nine.

Consider the simple AHP model shown in Figure B-1 (repeat of Figure 2-6) as an example for the demonstration of the AHP.

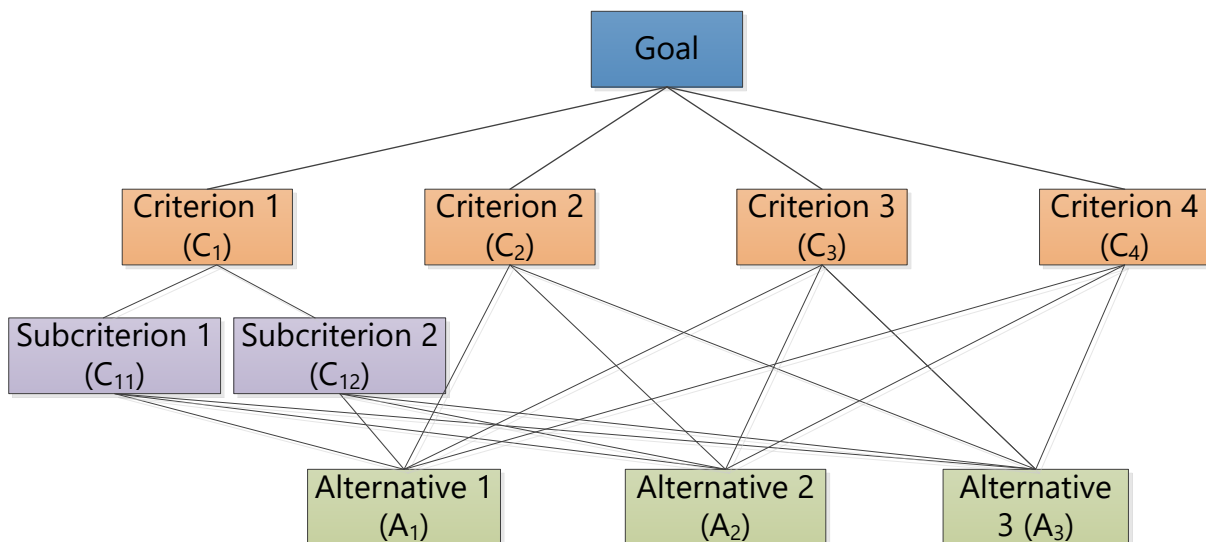


Figure B-1: A simple AHP model (repeat of Figure 2-6).

Step 2: Pair-wise comparisons and the judgement matrix

The second step of the AHP involves pair-wise comparisons to obtain a judgement matrix. The elements of a particular level are compared with respect to the element in the immediate upper level. Table B-1 shows a scale of relative importance from 1 to 9 that is used to conduct pair-wise comparisons of the elements [105]. An element receiving a higher rating with respect to another element is considered more important by the decision maker.

Table B-1: The comparison scale for the AHP (repeat of Table 2-5) [105].

Intensity of Importance	Definition
1	Equal importance
2	Slightly more important
3	
4	Moderately more important
5	
6	Strongly more important
7	
8	Extremely more important
9	

The pair-wise comparisons are captured in the form of judgement matrices. Each entry of the judgement matrix is governed by three rules, illustrated in Equation (12), Equation (13), and Equation (14) where a_{ij} refers to element i compared to element j .

$$a_{ij} > 0 \tag{12}$$

$$a_{ij} = \frac{1}{a_{ji}} \tag{13}$$

$$a_{ii} = 1 \tag{14}$$

The pair-wise comparisons of elements on each level will yield multiple judgement matrices. In the case of the simple AHP model illustrated in Figure B-1, the pair-wise comparisons result in seven judgement matrices, as shown in Table B-2 to Table B-8. Arbitrarily pair-wise comparison values are assigned for illustration purposes.

The first judgement matrix shown in Table B-2 is the comparison of the criteria with respect to the goal. The second judgmental matrix, Table B-3 is the comparison of the subcriteria (C_{11} and C_{12}) with

respect to their parent criterion (C_1). Table B-4 and Table B-5 are the comparisons of the alternatives (A_1 , A_2 , and A_3) with respect to the subcriteria (C_{11} and C_{12}). Similarly, Table B-6 to Table B-8 compare the alternatives with respect to Criterion 2 (C_2), Criterion 3 (C_3), and Criterion 4 (C_4), respectively.

Table B-2: Comparison of the criteria with respect to the goal of the decision-making problem.

	C_1	C_2	C_3	C_4
C_1	1	1	4	5
C_2	1	1	5	3
C_3	1/4	1/5	1	3
C_4	1/5	1/3	1/3	1

Table B-3: Comparison of the subcriteria with respect to Criterion 1 (C_1).

	C_{11}	C_{12}
C_{11}	1	1/3
C_{12}	3	1

Table B-4: Comparison of the alternatives with respect to Subcriterion 1 (C_{11}).

	A_1	A_2	A_3
A_1	1	2	3
A_2	1/2	1	2
A_3	1/3	1/2	1

Table B-5: Comparison of the alternatives with respect to Subcriterion 2 (C_{12}).

	A_1	A_2	A_3
A_1	1	1/3	5
A_2	3	1	7
A_3	1/5	1/7	1

Table B-6: Comparison of the alternatives with respect to Criterion 2 (C₂).

	A₁	A₂	A₃
A₁	1	1/9	1/5
A₂	9	1	4
A₃	5	1/4	1

Table B-7: Comparison of the alternatives with respect to Criterion 3 (C₃).

	A₁	A₂	A₃
A₁	1	2	5
A₂	1/2	1	3
A₃	1/5	1/3	1

Table B-8: Comparison of the alternatives with respect to Criterion 4 (C₄).

	A₁	A₂	A₃
A₁	1	3	9
A₂	1/3	1	3
A₃	1/9	1/3	1

Step 3: Consistency and weighting of criteria

Consistency

After the judgement matrices have been obtained, the local weights of each element can be calculated. The local weights are calculated using the eigenvector method. The judgement matrix is consistent if both the reciprocity rule in Equation (13) and the transitivity rule in Equation (15) are satisfied.

$$a_{ij} = a_{ik} \times a_{kj} \tag{15}$$

A consistent matrix satisfies Equation (16) where ω is the eigenvector (of order n) and λ is the eigenvalue. For a consistent matrix, $\lambda = n$.

$$A\omega = \lambda\omega \tag{16}$$

If the transitivity rule is not satisfied, there is some inconsistency in the matrix. Perfect adherence to the transitivity rule is hard to comply with since human judgements are involved based on verbal descriptions of the scale of importance [105]. In this case, Equation (16) is adapted as shown in Equation (17) where $\lambda_{max} \geq n$.

$$A\omega = \lambda_{max}\omega \tag{17}$$

Saaty [107] proposed a consistency index (CI) to evaluate the consistency of the judgmental matrix as shown in Equation (18)

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{18}$$

The consistency index is subsequently used to calculate the consistency ratio (CR) as shown in Equation (19)

$$CR = \frac{CI}{RI} \tag{19}$$

where RI is the random index. The random index is the average of 500 randomly filled matrices which is available in published tables, such as the one presented in Table B-9 [105].

Table B-9: Consistency indices for randomly generated matrices [105] (repeat of Table 2-7).

n	2	3	4	5	6
RI	0	0.58	0.9	1.12	1.24

Consistency ratios of 0.1 or below are considered acceptable [105].

Weighting of criteria

The local weights are calculated using the eigenvector method where the judgmental matrix is raised to powers that are successively squared each time. Each row is then summed and normalised. The procedure is terminated when the difference between the sums in two consecutive calculations is smaller than a prescribed value [107, 123]. The resulting eigenvector represents the local weights of the criteria.

If the consistency ratio is low, a good approximation for the eigenvector can be obtained as follows: the entries in each row of the judgement matrix are multiplied and the n^{th} roots of each product is calculated where n is the number of elements of the judgement matrix [105].

The n^{th} roots are summed, and the resulting value is used to normalise the values to add up to one. The normalised vector is a good approximation for the eigenvector and is indicative of the local weights for each element in the associated judgement matrix. The respective child elements under each parent element of the hierarchy should sum to one to verify that the local weights were assigned correctly.

To illustrate the assignment of local weights through the approximated eigenvector method, consider the judgement matrix from Table B-2. First, the entries in each row of the judgement matrix are multiplied as shown in Table B-10.

Table B-10: Approximated eigenvector for the judgement of the criteria relative to the goal.

	C₁	C₂	C₃	C₄	Product of rows	nth root of product	Local weights (Eigenvector ω)	Consistency ratio
C₁	1	1	4	5	20	2.115	0.415	
C₂	1	1	5	3	15	1.968	0.387	
C₃	0.25	0.2	1	3	0.15	0.622	0.122	0.087
C₄	0.2	0.333	0.333	1	0.022	0.386	0.076	
Totals						5.091	1.000	

Thereafter, the 4th root of each product is taken since there are 4 elements in the judgement matrix. The 4th root of each product is summed, and the eigenvector is approximated by dividing each 4th root of the product by the sum of all the root products. The resulting eigenvector is representative of the local weights assigned to each criterion. Table B-10 shows that, for this example, the order of importance in descending order is C₁, C₂, C₃, and C₄.

λ_{max} is required to calculate the consistency index for the judgmental matrix in Table B-10. The left-hand side of Equation (17), $A\omega$, is calculated as shown in Equation (20)

$$A\omega = \begin{bmatrix} 1.670 \\ 1.641 \\ 0.531 \\ 0.328 \end{bmatrix} \tag{20}$$

Four estimates for λ_{max} are made by dividing each component of the matrix in Equation (20) by the corresponding eigenvector element (ω) to satisfy Equation (17). The four resulting estimates for λ_{max} are thus 4.021; 4.244; 4.343; and 4.332. λ_{max} is subsequently calculated as the mean of the four

estimated values, namely 4.235. The resulting consistency index is calculated from Equation (18) as 0.078. The random index for the matrix is obtained from Table B-9 as 0.9 and using Equation (19), the consistency ratio is calculated as 0.087. Since the consistency ratio is less than 0.1, the judgement matrix in Table B-10 is considered consistent [105].

The same method is used to determine the local weights (eigenvectors) and the consistency ratio for the matrix in Table B-3. The local weights and the consistency ratio for the judgement matrix in Table B-3 are presented in Table B-11. The judgement matrix is consistent due to the low consistency ratio and thus the approximated eigenvector method is accurate.

Table B-11: Approximated eigenvector for the judgement of the subcriteria relative to C₁.

	C ₁₁	C ₁₂	Local weights (Eigenvector ω)	Consistency ratio
C ₁₁	1	0.333	0.25	0.000
C ₁₂	3	1	0.75	
Totals			1.000	

Figure B-2 shows the local weights of the criteria and subcriteria. The respective child elements under each parent element of the hierarchy should sum to one to verify that the local weights were assigned correctly.

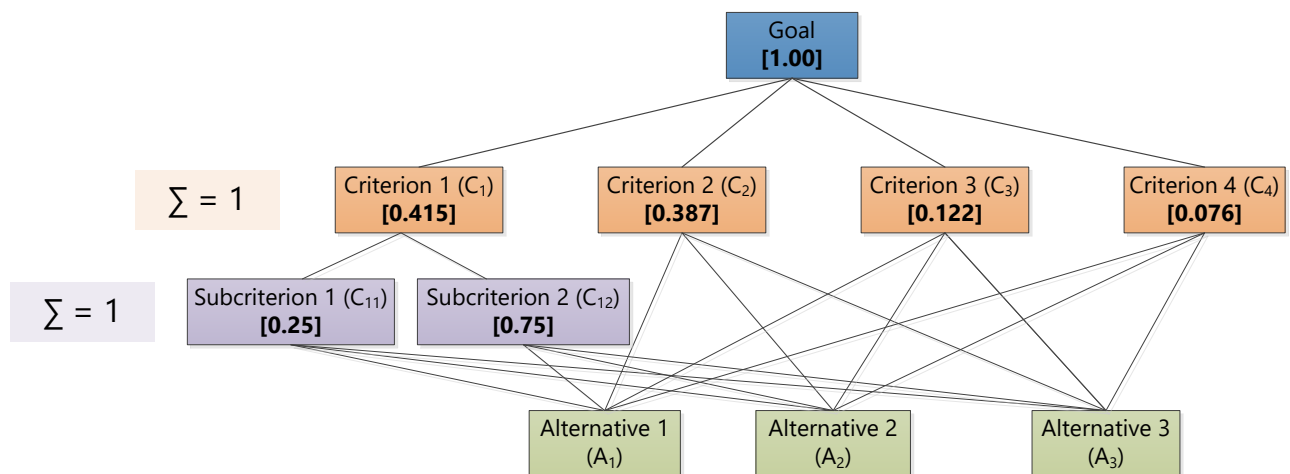


Figure B-2: The assignment of local weights to the criteria of the simple AHP model.

The global weights of each criterion and subcriterion with respect to the goal are calculated by multiplying its local weight with the local weight of the level above. Figure B-3 shows the assignment

of the global weights for the criteria and subcriteria. To confirm the accuracy of the global weight assignment, the child elements should sum to the global weight of the parent element.

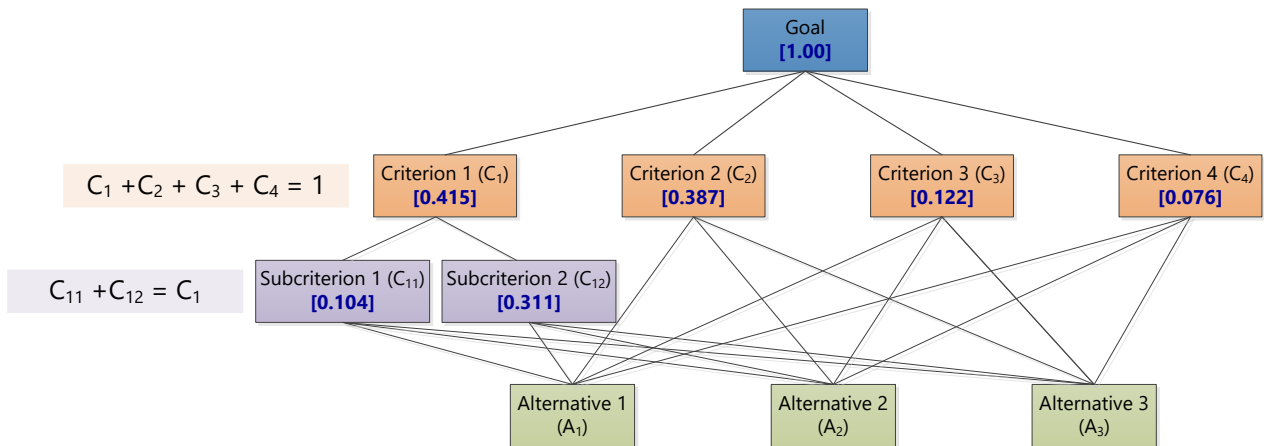


Figure B-3: The assignment of global weights to the criteria of the simple AHP model.

Step 4: Local weights of the alternatives

The same method as described in Step 3 can be used to determine the local weights (eigenvectors) and consistency ratios for the judgement matrices that evaluate the alternatives with respect to each criterion. However, the number of alternatives that can be compared and judged simultaneously without error is 7 ± 2 [104]. Thus, if the number of alternatives is more than nine, an excessive number of pair-wise comparisons would be required and the method described in Step 3 may lead to errors in judgement [105]. Additionally, alternatives may frequently be added or removed which would lead to a tedious, repetitive comparison process every time an alternative is added or removed.

Saaty [107] developed ratings models to resolve the issues of a large number of comparisons and frequently changing alternatives. Ratings scales are developed for each criterion with a rating assigned to a variety of situations that may occur for the specific criterion. A scale with three, five, seven or ten different values is recommended and the higher score should reflect greater convenience with respect to the alternative [105].

An example of a ratings scale with three values for the evaluation of the *Compatibility* of a proposed energy efficiency measure (EEM) is shown in Table B-12. The ideal situation for the *Compatibility* of a proposed EEM is that only minor adjustments are required to the existing infrastructure. Therefore, a rating of 3 is used for such a situation since a higher rating reflects a greater convenience.

Table B-12: An example of a ratings scale for evaluating the compatibility of a proposed EEM.

Compatibility	Rating
New infrastructure required or significant adaption of current infrastructure.	1
Notable adjustments to current infrastructure.	2
Minor adjustments to current infrastructure.	3

Similarly, an example of a ratings scale for the evaluation of the *Payback period (PP)* of a proposed EEM is shown in Table B-13. A lower *PP* is preferred and thus a rating of 3 is used for such a situation since a higher rating reflects a greater convenience.

Table B-13: An example of a ratings scale for evaluating the payback period of a proposed EEM.

Payback period	Rating
More than 3 years	1
Between 1 and 3 years	2
Less than 1 year	3

Consider the simple AHP model of Figure B-1 to illustrate the assignment of weights to the alternatives. Since the number of alternatives in this example is less than nine, the same method as described in Step 3 can be used to determine the local weights (eigenvectors) and consistency ratios for the remainder of the judgement matrices in Table B-4 to Table B-8. The local weights and the consistency ratios for each of the matrices are presented in Table B-14 to Table B-18. All of the judgement matrices are consistent due to the low consistency ratios and thus the approximated eigenvector method is accurate.

Table B-14: Approximated eigenvector for the judgement of the alternatives relative to C_{11} .

	A_1	A_2	A_3	Local weights (Eigenvector ω)	Consistency ratio
A_1	1	2	3	0.540	0.008
A_2	0.5	1	2	0.297	
A_3	0.333	0.5	1	0.163	
Totals				1.000	

Table B-15: Approximated eigenvector for the judgement of the alternatives relative C_{12} .

	A₁	A₂	A₃	Local weights (Eigenvector ω)	Consistency ratio
A₁	1	0.333	5	0.279	0.056
A₂	3	1	7	0.649	
A₃	0.2	0.14	1	0.072	
Totals				1.000	

Table B-16: Approximated eigenvector for the judgement of the alternatives relative to C_2 .

	A₁	A₂	A₃	Local weights (Eigenvector ω)	Consistency ratio
A₁	1	0.111	0.2	0.060	0.061
A₂	9	1	4	0.709	
A₃	5	0.25	1	0.231	
Totals				1.000	

Table B-17: Approximated eigenvector for the judgement of the alternatives relative to C_3 .

	A₁	A₂	A₃	Local weights (Eigenvector ω)	Consistency ratio
A₁	1	2	5	0.582	0.003
A₂	1/2	1	3	0.309	
A₃	1/5	1/3	1	0.109	
Totals				1.000	

Table B-18: Approximated eigenvector for the judgement of the alternatives relative to C_4 .

	A₁	A₂	A₃	Local weights (Eigenvector ω)	Consistency ratio
A₁	1	3	9	0.692	0.000
A₂	1/3	1	3	0.231	
A₃	1/9	1/3	1	0.077	
Totals				1.000	

Step 5: Final weights of alternatives

The local weights assigned to each element as outlined in Step 3 and Step 4 are aggregated to obtain the final weights of each of the alternatives on the bottom level of the simple AHP model shown in Figure B-1. The final weight of each alternative is calculated by Equation (21)

$$Final\ weight\ of\ A_m = \sum_j (w_{mj} \times I_j) \tag{21}$$

where A_m refers to alternative m , w_{mj} is the weight of alternative m with respect to criterion j , and I_j is the importance of criterion j .

If ratings models are used to evaluate the alternatives criteria with respect to the criteria, the final weights of the alternatives are summed, and the final score of each alternative is normalised to obtain the final priorities.

The final weight of each alternative of Figure B-1 is calculated by Equation (21). The final weights of each alternative shown in Table B-19 show that A_2 has the highest final weight. The alternative that best satisfied the goal in the illustrative example is thus A_2 , followed by A_1 and lastly A_3 .

Table B-19: The final weights of each of the alternatives in the illustrative example.

Final weights	
A₁	0.290
A₂	0.562
A₃	0.148
Total	1.000

C. APPENDIX C: ISO 5807 Flow diagram symbols (Chapter 2)

Appendix C.1 contains a summary of the ISO 5807:1985 flow diagram symbols. Some of the symbols are used in the flow diagrams throughout the document (Section 2.6).

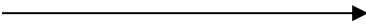



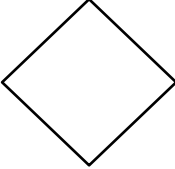

Appendix C.1:

- A summary of the ISO 5807:1985 flowchart symbols (Section 2.6).

Appendix C.1: ISO 5807 Flow diagram symbols

Flow diagrams are used throughout Section 2.6 to illustrate the decision-making process during the design of the structured approach. Table C-1 shows descriptions of common ISO 5807:1985 symbols [109] used for flowchart construction adapted from [124].

Table C-1: ISO common symbols used for the construction of flowcharts. Adapted from [124].

Symbol	Description
	<p>Flowline (Arrowhead): Shows the order of operation in the process.</p>
	<p>Process: Indicates a processing function.</p>
	<p>Data: A representation of data.</p>
	<p>Terminal: Indicates the start or the end of a process.</p>
	<p>Decision: Indicates a decision to be made with more than one outcome/path.</p>
	<p>Document: Represents human readable data such as printed output and data entry forms.</p>

D. APPENDIX D: Sample questionnaire (Chapter 2)

The weighting of the complexity criteria in Section 2.6.1 and the weighting of the prioritisation criteria in Section 2.6.2 are facilitated by means of a questionnaire. Appendix D.1 provides a sample questionnaire that respondents may use to weight the various criteria.

Appendix D.1:

- A sample questionnaire used for the weighting of complexity criteria and prioritisation criteria via pair-wise comparisons (Section 2.6).

Appendix D.1: Sample questionnaire

Prioritisation questionnaire

Goal of the questionnaire

The goal of the questionnaire is to assign weights to various energy efficiency measure (EEM) prioritisation criteria by pair-wise comparisons. The weighted criteria will then be used to prioritise competing industrial energy efficiency projects.

Background on the prioritisation method

The Analytical Hierarchy Process (AHP) was chosen as the prioritisation method. The AHP represents an accurate approach to quantifying the weights of decision criteria. The AHP method requires the problem to be modelled as a hierarchy. The participant compares each level of the hierarchy in a pair-wise manner. An example of the criteria hierarchy is provided in Figure D-1.

Participant requirements

The participant is requested to answer two questions. Question 1 requires the participant to disclose their highest academic qualification as well as years of experience in the energy management field. Question 2 requires the participant to compare prioritisation criteria and assigns weights according to the relative importance of one criterion over another. Question 2 is divided into three parts, namely Q2.1, Q2.2, and Q2.3.

Instructions for the completion of the questionnaire

1. Please answer Question 1 in the space provided.
2. Various project prioritisation criteria were researched and compiled into groups. Similar criteria were grouped into categories to form a hierarchy, as illustrated in Figure D-1. Each subquestion requires the participant to compare and score criteria from each group. Q2.1 and Q2.2 require the participant to compare and score technical and financial criteria, respectively. Q2.3 requires the participant to compare and score high-level criteria. Instructions for each question are provided at each question. Descriptions of the relevant criteria are provided at each question.

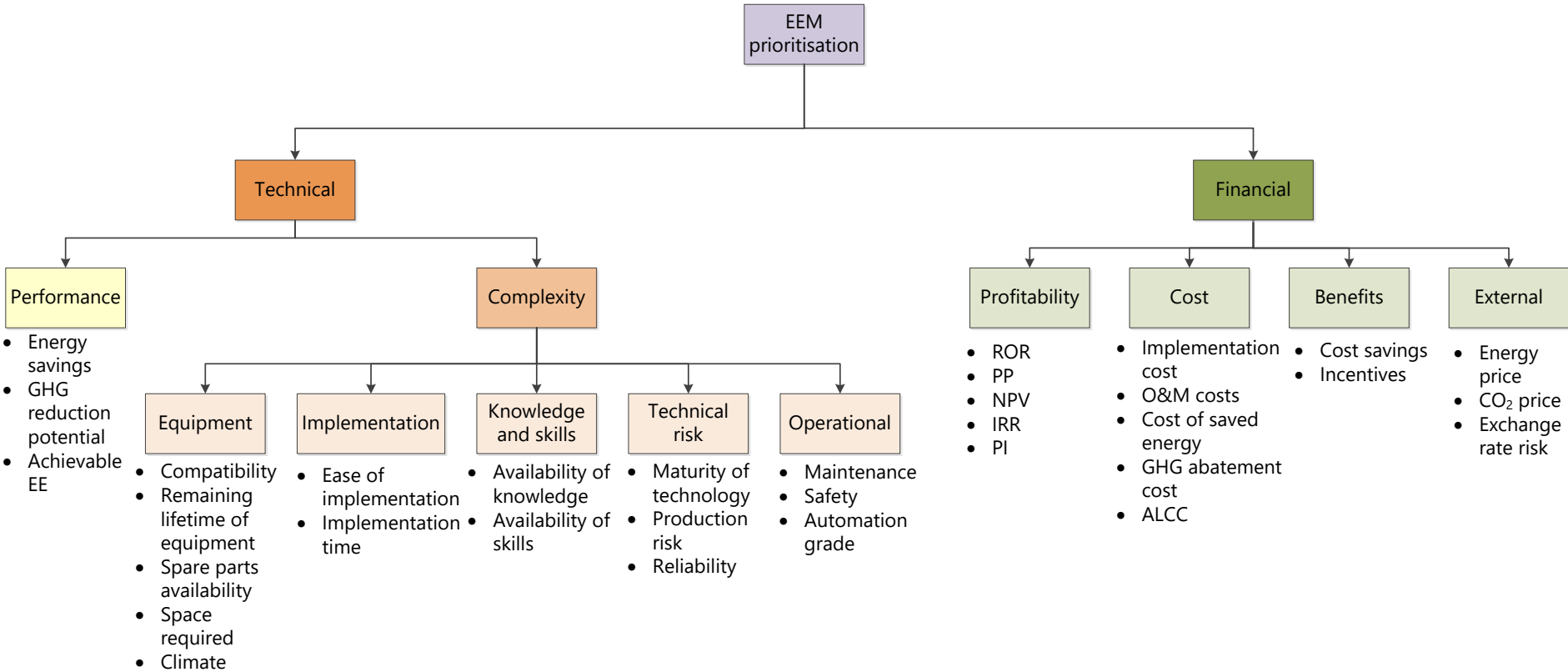


Figure D-1: The hierarchy of the prioritisation criteria.

Question 1

1.1 What is your highest academic qualification? _____

1.2 How many years of experience in energy management do you have? _____

Question 2

Table D-1 is used to score the prioritisation criteria.

Table D-1: The scoring scale used to weight the prioritisation criteria.

Scoring scale	
Scale	Definition
1	Equally important
2	Equally or slightly more important
3	Slightly more important
4	Slightly to much more important
5	Much more important
6	Much to far more important
7	Far more important
8	Far more important to extremely more important
9	Extremely more important

Question 2.1: Technical criteria

1. Descriptions of the technical criteria are provided in Table D-2.
2. Complete each subsection of Table D-3 to Table D-10 by choosing the criterion that is more important.
3. Assign a score to the chosen criteria according to the scale in Table D-1.
4. Additional criteria that were not considered can be added to the allocated space at the end of the question.

Table D-2: Descriptions of the technical prioritisation criteria.

Group	Criterion	Description of criterion
Performance	Energy savings	The amount of energy in units of kWh that is saved by the implementation of the Energy Efficiency Measure (EEM).
	Greenhouse gas (GHG) reduction potential	The quantifiable reduction in CO ₂ -equivalent emissions because of the implementation of the EEM.
	Achievable energy efficiency (EE)	An estimation of the performance of the EEM by determining the energy use before and after the implementation of the EEM to the output obtained.
Complexity	-	All of the complexity factors described below in totality.
Equipment	Compatibility	The level of compatibility of the EEM to existing infrastructure.
	Remaining lifetime of equipment	The age of existing equipment that is either retrofitted or replaced by the EEM. Some equipment can only be replaced at the end of their lifecycle.
	Spare parts availability	The availability of spare parts for preventative and corrective maintenance.
	Space required	An assessment of the availability of space for the implementation of the EEM. It includes the difficulty of the procurement of additional required land.
	Climate	The influence of the location climate on the technical performance of the EEM. For example, higher altitude levels can lead to an increased pressure drop over equipment.
Implementation	Ease of implementation	The level of technical and logistical difficulty in implementing the EEM.
	Implementation time	The time that it will take to fully implement the EEM.

Group	Criterion	Description of criterion
Knowledge and skills	Availability of knowledge	The availability of local or in-house knowledge of the proposed EEM as well as the system that it will be implemented on.
	Availability of skills	The availability of existing or easily required skills for the implementation, operation, and maintenance of the proposed EEM.
Technical risk	Maturity of technology	The technology or EEM has been in use for a long time and most of its initial faults and inherent problems have been reduced or resolved. Mature technology usually has wide-spread use.
	Production risk	The likelihood that the EEM will pose a risk to production quality or quantity as a result of disruption time or other factors.
	Reliability of technology	The capacity of the EEM to perform as designed; the resistance of the EEM to failure.
Operational	Maintenance	The level of maintenance that the EEM requires.
	Safety	The level of danger during the installation, operation, and maintenance of the EEM.
	Automation grade	The level of human input required for the operation of the EEM after implementation.

Table D-3: Pair-wise comparisons of the *Technical* criteria.

Technical criteria			
Criteria		Which criterion is more important?	By how much?
Performance	Complexity	Choose an item.	Choose an item.

Table D-4: Pair-wise comparisons of the *Performance* criteria.

Performance			
Criteria		Which criterion is more important?	By how much?
Energy savings	GHG reduction potential	Choose an item.	Choose an item.
Energy savings	Achievable EE	Choose an item.	Choose an item.
GHG reduction potential	Achievable EE	Choose an item.	Choose an item.

Table D-5: Pair-wise comparisons of the *Complexity* criteria.

Complexity criteria			
Criteria		Which criterion is more important?	By how much?
Equipment	Implementation	Choose an item.	Choose an item.
Equipment	Knowledge and skills	Choose an item.	Choose an item.
Equipment	Technical risk	Choose an item.	Choose an item.
Equipment	Operational	Choose an item.	Choose an item.
Implementation	Knowledge and skills	Choose an item.	Choose an item.
Implementation	Technical risk	Choose an item.	Choose an item.
Implementation	Operational	Choose an item.	Choose an item.
Knowledge and skills	Technical risk	Choose an item.	Choose an item.
Knowledge and skills	Operational	Choose an item.	Choose an item.
Technical risk	Operational	Choose an item.	Choose an item.

Table D-6: Pair-wise comparisons of the *Equipment* criteria.

Equipment			
Criteria		Which criterion is more important?	By how much?
Compatibility	Remaining lifetime of equipment	Choose an item.	Choose an item.
Compatibility	Spare parts availability	Choose an item.	Choose an item.
Compatibility	Space required	Choose an item.	Choose an item.
Compatibility	Climate	Choose an item.	Choose an item.
Remaining lifetime of equipment	Spare parts availability	Choose an item.	Choose an item.
Remaining lifetime of equipment	Space required	Choose an item.	Choose an item.
Remaining lifetime of equipment	Climate	Choose an item.	Choose an item.
Spare parts availability	Space required	Choose an item.	Choose an item.
Spare parts availability	Climate	Choose an item.	Choose an item.
Space required	Climate	Choose an item.	Choose an item.

Table D-7: Pair-wise comparisons of the *Implementation* complexity criteria.

Implementation complexity			
Criteria		Which criterion is more important?	By how much?
Ease of implementation	Implementation time	Choose an item.	Choose an item.

Table D-8: Pair-wise comparisons of the *Knowledge and skills* criteria.

Knowledge and skills			
Criteria		Which criterion is more important?	By how much?
Availability of knowledge	Availability of skills	Choose an item.	Choose an item.

Table D-9: Pair-wise comparisons of the *Technical risk* criteria.

Technical risk			
Criteria		Which criterion is more important?	By how much?
Maturity of technology	Production risk	Choose an item.	Choose an item.
Maturity of technology	Reliability of technology	Choose an item.	Choose an item.
Production risk	Reliability of technology	Choose an item.	Choose an item.

Table D-10: Pair-wise comparisons of the *Operational* criteria.

Operational			
Criteria		Which criterion is more important?	By how much?
Maintenance	Safety	Choose an item.	Choose an item.
Maintenance	Automation grade	Choose an item.	Choose an item.
Safety	Automation grade	Choose an item.	Choose an item.

Optional: Additional criteria not considered: _____

Question 2.2: Financial criteria

1. Descriptions of the financial criteria are provided in Table D-11.
2. Complete each subsection of Table D-12 to Table D-16 by choosing the criterion that is more important.
3. Assign a score to the chosen criteria according to the scale in Table D-1.
4. Additional criteria that were not considered can be added to the allocated space at the end of the question.

Table D-11: Descriptions of the financial prioritisation criteria.

Group	Criterion	Description of criterion
Profitability	Rate of Return (ROR)	The ratio of the average financial benefit expected to the initial investment amount.
	Payback Period (PP)	The amount of time it takes to recover the cost of the investment.
	Net Present Value (NPV)	The difference between the present value of the cash inflows and the cash outflows.
	Internal Rate of Return (IRR)	The discount rate that yields a zero NPV of all cash flows for the considered EEM.
	Profitability index (PI)	The ratio of the payoff to the investment of the EEM.
Cost	Implementation cost	The cost to implement the EEM, including capital cost and installation costs.
	Operation and maintenance (O&M) cost	The costs related to the operation and maintenance of the implemented EEM.
	Cost of saved energy	The ratio of the total annualised cost of implementing and operating an EEM to the annual potential energy saved as a result of the measure, i.e. the annual cost of saving one unit of energy.
	GHG abatement cost	The ratio of the equivalent annual investment cost to the GHG emission reduction potential, i.e. the annual cost of saving one tonne of CO ₂ -equivalent.
	Annualised lifecycle cost (ALCC)	An estimation of the total costs, including implementation, operating, and maintenance costs over the lifetime of the EEM.
Benefits	Cost savings	The monetary cost savings as a result of implementing the EEM, for example reduced fuel demand leading to lower costs.
	Incentives	The availability of qualifying incentives for the EEM such as tax incentives and government funding.

Group	Criterion	Description of criterion
External	Energy price	The cost of procuring one unit of energy.
	CO ₂ price	The cost per tonne of CO ₂ -equivalent emitted.
	Exchange rate risk	The likelihood of the change in the exchange rate of equipment or services purchased in a currency different from the country where the EEM is implemented.

Table D-12: Pair-wise comparisons of the *Financial* criteria.

Financial criteria			
Criteria		Which criterion is more important?	By how much?
Profitability	Cost	Choose an item.	Choose an item.
Profitability	Benefits	Choose an item.	Choose an item.
Profitability	External	Choose an item.	Choose an item.
Cost	Benefits	Choose an item.	Choose an item.
Cost	External	Choose an item.	Choose an item.
Benefits	External	Choose an item.	Choose an item.

Table D-13: Pair-wise comparisons of the *Profitability* criteria.

Profitability			
Criteria		Which criterion is more important?	By how much?
ROR	PP	Choose an item.	Choose an item.
ROR	NPV	Choose an item.	Choose an item.
ROR	IRR	Choose an item.	Choose an item.
ROR	PI	Choose an item.	Choose an item.
PP	NPV	Choose an item.	Choose an item.
PP	IRR	Choose an item.	Choose an item.
PP	PI	Choose an item.	Choose an item.
NPV	IRR	Choose an item.	Choose an item.
NPV	PI	Choose an item.	Choose an item.
IRR	PI	Choose an item.	Choose an item.

Table D-14: Pair-wise comparisons of the *Cost* criteria.

Cost			
Criteria		Which criterion is more important?	By how much?
Implementation cost	O&M cost	Choose an item.	Choose an item.
Implementation cost	Cost of saved energy	Choose an item.	Choose an item.
Implementation cost	GHG abatement cost	Choose an item.	Choose an item.
Implementation cost	ALCC	Choose an item.	Choose an item.
O&M cost	Cost of saved energy	Choose an item.	Choose an item.
O&M cost	GHG abatement cost	Choose an item.	Choose an item.
O&M cost	ALCC	Choose an item.	Choose an item.
Cost of saved energy	GHG abatement cost	Choose an item.	Choose an item.
Cost of saved energy	ALCC	Choose an item.	Choose an item.
GHG abatement cost	ALCC	Choose an item.	Choose an item.

Table D-15: Pair-wise comparisons of the *Benefits* criteria.

Benefits			
Criteria		Which criterion is more important?	By how much?
Cost savings	Incentives	Choose an item.	Choose an item.

Table D-16: Pair-wise comparisons of the *External* criteria.

External			
Criteria		Which criterion is more important?	By how much?
Energy price	CO ₂ price	Choose an item.	Choose an item.
Energy price	Exchange rate risk	Choose an item.	Choose an item.
CO ₂ price	Exchange rate risk	Choose an item.	Choose an item.

Optional: Additional criteria not considered: _____

Question 2.3: High-level criteria

1. Complete each subsection by choosing the criterion that is more important.
2. Assign a score to the chosen criteria in Table D-17 according to the scale in Table D-1.
3. Additional criteria that were not considered can be added to the allocated space at the end of the question.

Table D-17: Pair-wise comparison of the high-level prioritisation criteria.

High-level criteria			
Criteria		Which criterion is more important?	By how much?
Financial criteria	Technical criteria	Choose an item.	Choose an item.

Optional: Additional criteria not considered: _____

E. APPENDIX E: Case study EEMs (Chapter 3)

A large industrial facility was chosen as the case study to validate the developed structured approach. This Appendix contains additional information for the case study presented in Section 3.2. Appendix E.1 contains details on the proposed energy efficiency measures (EEMs) for the facility.

Appendix E.1:

- Generic names and descriptions of the proposed EEMs or the case study (Section 3.2).

Appendix E.1: Proposed EEMs

A large industrial facility was chosen as the case study. To protect the privacy and the anonymity of the facility selected as the case study, generic names and project descriptions were assigned to the list of proposed EEMs. The anonymised list of proposed EEMs is shown in Table E-1.

Table E-1: Anonymised information of the proposed EEMs for the case study.

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
1	Steam generation pressure reduction	Reduce steam generation pressure	Process control					<1	
2	Steam generation pressure increase	Increase existing steam generation pressure	Process control					1-3	
3	Lower steam exhaust pressure supply	Lower the steam exhaust pressure supply to meet demands.	Supply-demand matching					1-3	
4	VSD on cooling towers	Installation of VSD on plant cooling towers.	Supply-demand matching						
5	APC KPI monitoring		Process control						
6	Steam to flares optimisation	Investigate optimisation of the use of steam in flares.	Supply-demand matching	38 933 333	15 471				
7	Improve economics of steam turbine generator 2	Improve economics of generator through fuel switch.	Supply-demand matching					<1	
8	Boiler Project	Waste gas to flare can be used in boiler to produce steam.	Heat recovery/CHP	109 013 333	43 318		286	4	103.6

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
9	Compressor electricity savings	Current compressor is oversized. Modification of existing compressor.	Supply-demand matching						
10	Optimise on steam usage	Investigate steam usage on all major steam users.	Supply-demand matching	1 000					
11	Steam turbine operational improvement	Replace steam turbine with electric drive.	New technology						
12	Additional/replacing processing capacity study	Investigate the need for additional processing capacity or the feasibility of replacing current equipment with the latest and most efficient technology.	New technology						
13	Plant integration and redundancy		Supply-demand matching						
14	General furnace optimisation		Retrofitting						
15	Oil leak investigation		Maintenance						
16	Steam turbine conversion	Conversion of steam driven turbines to electricity driven.	New technology						

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
17	Optimise on H2 export		Supply-demand matching						
18	Pinch study		Supply-demand matching						
19	VSDs on compressors	Consider variable speed drives for existing compressors for energy savings.	Supply-demand matching						
20	Production APC	Advanced process control to reduce production wastage.	Process control						
21	Processing flare stream	Feasibility of diverting utilising by product at different section.	Supply-demand matching				10	0.5	
22	Stack Heat recovery	The furnaces are discharging heat through the stack to atmosphere. There is an opportunity to recover heat and generate steam.	Heat recovery/CHP				10	1.4	
23	Process optimisation and leak detection	Investigate optimisation options to reduce wastages. Investigate possible product leaks between two sections.	Maintenance				20	2.2	

A structured approach to prioritise industrial energy efficiency measures by assessing feasibility criteria

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
24	Steam recovery from blowdown	Steam recovery from blowdowns to supplement steam consumption.	Heat recovery/CHP					1-3	
25	Recover process by-products	Existing process by-products are discarded. Best practice is to recover this by-product and generate dilution steam. Saves water and small amount of steam.	Minimising losses					1-3	
26	Reduce unnecessary standby of equipment	Improve reliability of input materials to reduce unnecessary standby of equipment.	Supply-demand matching						
27	Waste heat boiler replacement	Waste heat boiler replacement to re-instate integrity and improve steam supply.	New technology	101 226 667	40 224		19	1.1	96.2
28	Production efficiency improvement at alternative section.	Route feed from the current section to alternative section to improve production efficiency.	Supply-demand matching	46 720 000	18 565				
29	Routing of spent by-product to additional section for re-use	Re-use the spent by-product at plant E. Save on required fresh make-up quantities.	Supply-demand matching	46 720 000	18 565				

A structured approach to prioritise industrial energy efficiency measures by assessing feasibility criteria

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
30	Conversion of storage	Convert existing storage to store alternative products and reduce wastages.	Retrofitting	14 342 500	2 861		10	0.83	
31	Replacement of driers	Replacement of driers with higher design pressure to reduce wastage.	New technology	7 744 950	1 545		10	2.3	
32	Return steam condensate	Increase steam condensate recovery from the process to reduce/remove additional cooling of condensate in cooling water exchanger. Improve water management to re-use process condensate instead of clean condensate.	Minimising losses	5 450 667	2 166			1-3	
33	Preheating of process feed	Further preheating of the process feed using the hot liquid for the 2nd effect.	Heat recovery/CHP	3 893 333	1 547			>3	
34	Preheating of process feed 2	Use steam condensate from the process for feed preheating.	Heat recovery/CHP	5 450 667	2 166			>3	
35	Process energy recovery	Investigate if high temperature streams can be used to pre-heat feed streams and reduce overall energy consumption.	Heat recovery/CHP						

A structured approach to prioritise industrial energy efficiency measures by assessing feasibility criteria

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
36	Use of waste heat to heat dearator feed water	Use of waste heat to heat dearator feed water to reduce de-aeration steam requirements.	Heat recovery/CHP	34 624 581	18 815			1-3	
37	Improve vacuum of condensing turbine	Improve vacuum of condensing turbine by reducing cooling water temperature. This will reduce steam use.	Retrofitting	44 384 000	17 637			1-3	
38	Optimisation of production process	Evaluate and identify levers in the process to increase production. Reduce steam usage and minimising the pressure drop over the stages.	Process control	23 360 000	9 282				
39	Recovery of wasted by-products		Heat recovery/CHP				90	18	
40	Utilities Optimisation of production process		Process control						
41	Utilities Optimisation of product value chain		Process control						
42	Fuel APC	Re-commissioning of APC on fuel system to reduce wastage and minimise cost.	Process control						

A structured approach to prioritise industrial energy efficiency measures by assessing feasibility criteria

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
43	Material lifetime extension and supplier evaluation	Extend current turnaround of materials by 4 months.	New technology						
44	Reduced steam consumption	Low temperature of steam at consumption point requires excessive amount of extra steam to reach its minimum temperature. Solution: Compare smaller line installation versus an economiser that heats up other steam sources and choose option that minimises the cost.	Retrofitting	38 933 333	15 471		10	1.3	
45	Material lifetime extension and supplier evaluation 2	Materials are due for replacement. Potential to install improved materials for longer runlength.	New technology						
46	Let-down turbine	Opportunity to install turbines to better utilise energy from the steam network.	New technology	151 200 000			226	2.1	143.6
47	Cooling tower pump performance evaluation	Verify operating philosophy for cooling tower pumps to improve pump reliability.	Process control				15	25	
48	Equipment level control	Review level control capacities to prevent wastage due to high	New technology						

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
		levels and trips on the compressor.							
49	Install vibration monitoring system	Installation of monitoring systems on all critical rotating equipment.	Supply-demand matching				5.2		
50	Material change 2	Change material to a low temperature requirement material, reducing steam requirement for pre-heating.	Process control	3 893 333	1 547		2	2.9	3.7
51	Energy efficient lighting/ warehouse lighting	Replace lights in warehouse and workshop to reduce energy consumption.	Process control	2 433 333			2	4	2.31
52	Initiator rationalisation	Steam reduction in compressor oil by reduced consumption.	Process control						
53	Rationalisation of product components		Retrofitting						
54	Pellet water flow reduction	Pellet water system flow reduction on the plant to prevent excessive vibration on the cutter. Reduction in energy consumption by moving closer to the best efficiency point.	New technology						

A structured approach to prioritise industrial energy efficiency measures by assessing feasibility criteria

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
55	Review production system	Review production system design to eliminate losses to waste.	Supply-demand matching				1	2	
56	Secondary compressor oil rationalisation	Evaluate replacement of compressor. Potential cost reduction in compressor oil by reduced consumption.	Supply-demand matching						
57	Steam vent reduction / re-use	Utilise steam vent elsewhere on the plant/site and not vent it to atmosphere.	Minimising losses						
58	Steam trap audit and maintenance	Common steam trap monitoring and maintenance programme across the whole site encompassing the utility system and the individual plants.	Process control	62 293 333	24 753		37	<1	59.2
59	Office energy and plant lighting	Replace office and plant lighting with energy efficient lighting.	Supply-demand matching						
60	Steam trap audit and maintenance - AMPLIFIED	The steam traps and the condensate manifolds will be repaired and replaced.	Minimising losses	145 610 667	57 861				
61	Heater/Furnace optimisation	1% fuel gas optimisation of heater/furnace.	Maintenance	1 202 066 667	323 792				

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
62	Electric drive optimisation (including VSD on cooling towers)	Implementation of VSD technology and energy efficient drives on the cooling towers.	Minimising losses	11 709 000			20	1.3	
63	Thermal insulation maintenance	Thermal insulation maintenance sitewide.	Minimising losses	23 360 000	9 282				
64	Heat exchanger/fan cleaning	Heat exchanger/fan cleaning sitewide.	Supply-demand matching	31 146 667	12 377				
65	Steam turbine optimisation	Steam turbine optimisation.	Supply-demand matching	23 360 000	9 282				
66	Steam leak detection program	Steam leak detection program to identify and repair steam leaks.	New technology	7 786 667	3 094				
67	Excess by-product recovery to use as fuel.		Heat recovery/CHP						
68	Reduce steam temperatures	The steam at the consumption point too hot for the piping. Reducing the temperature safely and sustainably will require control system changes.	Supply-demand matching						

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
69	Replace motors with high efficiency motors (pumps etc)		Minimising losses						
70	Instrument air line	Installation of a 2" air line to the equipment to improve reliability and quality of instrument air.	Minimising losses						
71	Boiler steam savings	Frequent failures have led to reduced availability of boilers and excessive consumption of spares. Installation of additional equipment in conjunction with a change in some components will improve reliability.	Supply-demand matching	62 293 333	24 753				
72	Further de-bottlenecking of the steam supply	Monitor and model the steam system in order to further identify de-bottlenecking opportunities. This will allow potential waste heat sources to export to the network.	Supply-demand matching	46 720 000	18 565				
73	Re-route of steam condensate leak		Heat recovery/CHP						

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
74	Boiler oil usage reduction initiatives	Reduce the amount of oil used for start-ups and general boiler stability.	Supply-demand matching						
75	Utilise alternative input material	Use of cheaper alternative material (could have a negative cost) to replace current more expensive materials.	Process control					<1	
76	Replace let down deaeration steam	Send deaerated boiler feed water to additional sections to replace consumption of current deaeration steam using the existing water lines.	Retrofitting	30 918 639	15 780			<1	
77	Low-pressure steam generation 3	Investigate possible low-pressure steam options for increased generation.	Retrofitting	35 040 000			95	2.1	
78	Recover low-pressure steam.	Recover low-pressure steam at process.	New technology						
79	Increase availability of boilers	Increase availability of boilers to improve utilisation and outputs.	Process control	903 253 333	358 921			<1	
80	Optimise turbine loads	Optimise turbine loads to maximise generation using advanced modelling.	Supply-demand matching					<1	

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
81	Target higher steam temperature	Target higher steam temperature into process to increase outputs.	Supply-demand matching						
82	Improve vacuum in condensers 2	Improve vacuum in condensers to a constant to increase outputs (review ejector system, hot spots in condenser and minimise cooling water temperature).	Supply-demand matching					<1	
83	Optimisation of pump sets	Optimisation of pump sets - by increasing all the impeller sizes on these pumps the VSD speeds can be limited to design and therefore reduce motor failures.	New technology				0.5		
84	Boiler feed water pump optimisation		Heat recovery/CHP						
85	Fuel Trial	Fuel treatment chemical to increase fuel efficiency, minimize maintenance costs, protect equipment from failure due to erosion corrosion (i.e. caused by excessive soot blowing) and to control/prevent ash clogging.	New technology				10	0.5	

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
86	Optimisation of equipment	With the optimisation of equipment units, there is an increase in efficiency. The additional benefit is reduced maintenance and replacement of equipment.	Supply-demand matching				40	2.2	
87	Acidification of brine	Reducing the pH of the brine to improve the plant efficiency performance.	Process control				9	9	
88	Cooling water pumps switch-off	Plant runs in campaigns: 3 cooling water pumps are required when online. One pump could be switched off when the unit is offline.	Process control	555 556					
89	Material compression optimisation	Energy saving with use of one compressor.	Heat recovery/CHP	2 400 000			5.5	2.5	2.3
90	Optimise use of air compressors	Energy saving with use of correct number of compressors. Replacing six old compressors and two other compressors over the next four years.	Retrofitting	180 556			16	8	

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
91	Next generation equipment	Necessary upgrade from old generation equipment to new generation.	Heat recovery/CHP	5 000 000			25	25	
92	Improved steam utilisation	Upgrade evaporator vented steam to a usable low-pressure steam grade by utilising thermo-compressor technology.	Process control	26 634 293	12 377				
93	Technology conversion.	Convert technology when the equipment must be changed.	Retrofitting	2 388 889			26	52	
94	Chiller run time optimisation	The chiller plant functions to lower the cooling water supply temperature to the reaction unit. The chiller is not required at low ambient temperatures. The chiller plant is taken offline for three months during the winter.	Heat recovery/CHP	4 500 000					
95	Processing control	Feedforward control of processing unit to optimise material usage.	Supply-demand matching	1 111 111					
96	Increase material usage to processing unit	Increase material usage to processing unit from other units to save fuel costs.	Supply-demand matching	1 111 111					

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
97	Steam wastage minimisation	Due to heat transfer limitations in the reactor cooling coils, much of the steam generated in the coils is vented to atmosphere in order to maintain a low steam drum pressure. Installation of additional control valve to enable steam recovery to the plant header at low steam drum pressures.	Retrofitting	46 720 000	18 565		2	0.2	44.4
98	Installation of extra tubes at processing section	The processing section is undersized and the required heat transfer is not obtainable especially during end-of-run periods. Installing additional tubes and possibly converting to a 2-pass section can increase the heat transfer.	Supply-demand matching	2 013 333	800		4	2.7	
99	Recovery of steam to network - Phase I	Utilising thermo-compressor technology, the steam from steam drum can be exported to the network in order to back-out current steam wastages.	Process control	46 720 000	18 565		13	0.6	44.4

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EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
100	Reduction of recycle steam	Reduction of recycling of processing steam.	Process control	15 573 333	6 188		5	1.7	
101	Reduction in back-flushings recycle stream		Process control				10	5	
102	Recovery of steam-to-steam network - Phase II	Phase 2 of utilising thermo-compressor technology. The steam from steam drum can be exported to the network in order to back-out current steam wastages.	Process control	155 733 333	61 883		13	0.7	
103	Change steam to lower pressure supply	Change reboilers which can operate at lower pressure steam.	Supply-demand matching	3 114 667	1 238				
104	Steam optimisation at processing sector.	The desuperheater will exclusively supply the ejectors with steam. The consumption of steam will reduce.	Process control	3 893 333	1 547		1	0.3	3.7
105	Reduction of power usage from recycle compressor	The VSD compressor uses approximately R 1 million/month more in electricity compared to the similar duty recycle gas compressor on another plant.	New technology				30	1.5	

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
106	Reduction chilled water pumps capacity	Chilled water pumps are oversized as a result they consume more energy than required. Cutting the impellor will not yield required capacity therefore new, small pumps must be installed.	Minimising losses	876 000			7	10	0.83
107	Lower operating pressures within process.	Lowering operating pressure to decrease steam consumption requirement.	Supply-demand matching	7 786 667	3 094				
108	Electricity reduction on process unit	Optimisation of electricity usage on the process unit.	Process control						
109	Fuel reduction to furnace	Optimisation of fuel usage to the furnace.	Process control						
110	Fuel reduction on burner	Optimisation of fuel usage on the burner.	Retrofitting						
111	Steam use optimisation	By optimizing the control loop and minor piping changes, a current vent can be closed, and steam use can be used more efficiently.	Process control	38 933 333	15 471		10	2.9	37.0
112	Process steam usage reduction	Optimisation of steam usage at the process units.	Supply-demand matching	7 786 667	3 094				

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
113	Conversion of steam driven turbines	Conversion of steam driven turbines to electrical motors, savings on steam.	Process control						
114	Reduction/mitigation of major Incidents 1	Baseline improvement and wastage reduction by controlling major incidents using asset management.	Retrofitting	65 041 444	32 896				
115	Maximise import of steam from other sections.	Increase transfer of steam within process (problem with non-return valve now fixed). Reduce steam consumption and reduce site steam vent. Improve communication between the plants to maximise transfer.	Supply-demand matching	105 120 000	41 771			<1	
116	Increasing deaerator operating pressures		Heat recovery/CHP	62 293 333	24 753				
117	Reduce steam venting in process.	There is a steam vent that can be reduced by increasing the deaerator operating pressure.	Retrofitting	52 170 667	20 731			<1	
118	Increase deaerator operating pressure	Increase deaerator operating pressure to increase steam generation and reduce steam import.	New technology	38 154 667	15 161			<1	

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EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
119	Reduce cooling water turbine extraction pressure	Reducing the steam towards another level will reduce the steam required.	Heat recovery/CHP	23 360 000	9 282			<1	
120	Reduce pressure of steam generation	Reduce pressure of steam generation in the plant. Reducing pressure of steam generation will increase temperature driving forces and recover more heat from the process.	Heat recovery/CHP	7 008 000	2 785			<1	
121	Reduce dilution steam ratio	Reduce dilution steam ratio in main process units towards 0.3.	Minimising losses	54 506 667	21 659			<1	
122	Improve efficiency of boilers and optimise loads	Improve efficiency of boilers and optimise loads.	Minimising losses	249 173 333	99 013			<1	
123	Improve vacuum in condensing turbines X 3	Change current vacuum in condensing turbines to best practice pressure and temperature.	Heat recovery/CHP	42 048 000	16 708		45	<1	39.9
124	Water injection into compressor	High inter-stage compressor temperatures increase power requirements in compressor and steam loads on compressor turbines. Use of demineralised water injected	Heat recovery/CHP	4 672 000	1 856			<1	

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
		into inter-stage of compressor will reduce temperature and power requirements.							
125	Increase lines size or thermocompressor	Increase lines size of thermocompressor to overcome hydraulic problem of steam import above existing limit.	Heat recovery/CHP	84 096 000	33 417			<1	
126	Reduce steam pressure for power generation	Reduce the outlet pressure of steam from to generate more power.	New technology	11 193 333	1 176			<1	
127	Thermocompressor: increased steam pressures	Use thermocompressor to increase the steam pressure.	Retrofitting	54 506 667	21 659		80	1-3	51.8
128	Refrigerant to vaporise materials	Use of refrigerant to vaporise material feed rather than use steam.	Retrofitting	18 688 000	7 426			<1	
129	Superheat steam	Superheat steam generated from process to use in process instead of importing steam.	Heat recovery/CHP	31 146 667	12 377			1-3	
130	Swap power station vent	For previous projects, steam savings realised by generating more power. This increases the steam vent and thus power generation is not very efficient.	Retrofitting	164 688 000				1-3	

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
		Install a condensing turbine to take this excess steam and reduce the steam vent to zero.							
131	Reopening low pressure induction	Reopening low pressure induction on power generation turbines.	Process control	276 232 000	102 107			<1	
132	Minimise steam for superheating.	Minimise steam for superheating and use this steam to generate more power.	Process control	21 024 000	8 354			<1	
133	Heat sinks	Identifying suitable heat sinks in multiple sections for the steam network.	Supply-demand matching					<1	
134	Eliminate steam vent	Eliminate steam vent by increasing steam deaerator pressure.	Supply-demand matching	70 080 000	27 847			<1	
135	Indirect heating of boiler feed water	Use of low-pressure steam for indirect heating of boiler feed water downstream of deaerator.	New technology					<1	
136	Waste heat to increase steam generation	Use of waste heat to increase steam generation.	Supply-demand matching					>3	
137	Replace pass out turbine	Replace pass out turbine with complete condensing turbine.	New technology					>3	

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
138	Reduce pressure drop in steam feed line	Reduce pressure drop in steam feed line to condensing turbine.	New technology	1 557 333	619			>3	1.29
139	Waste steam reduction	Include waste steam reduction benefit in incinerator project.	New technology					1-3	
140	Steam generation from by-products	Currently considering generating steam from a waste heat boiler to recover heat from 600 C by-product.	Retrofitting	30 368 000	12 377			>3	25.90
141	Move air cooler downstream	Move air cooler downstream to side reflux to reduce pressure drop and save power in compressor.	Retrofitting	3 114 667	1 238			>3	2.96
142	Process quality improvement: reduce off spec and duration	Improve furnace operation and waste management procedure.	Minimising losses						
143	Optimise loading		New technology						
144	Steam savings	Steam savings realised on process equipment.	New technology	31 146 667	12 377				
145	Variable speed drives on boiler fans		Process control						

EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
146	High efficiency Raw water pumps	Installation of high efficiency raw water pumps.	Supply-demand matching	3 197 400					
147	Steam Heat Integration Phase 1	Excess steam that would have been vented is used to preheat boiler feed water.	Heat recovery/CHP	179 781 480	97 696		47.7	5.3	170.8
148	Renewable energy - Phase 1		Process control						
149	Renewable energy - Phase 2		New technology						
150	Renewable Energy - Phase 3		Heat recovery/CHP						
151	Plant at CO ₂ usage		Process control						
152	Vortex inducers on waste heat boiler		Process control	23 360 000	9 282				
153	Variable speed drives on cooling water fin fans		Supply-demand matching	5 925 000					
154	Solar installations on offices		Supply-demand matching	399 456					
155	Specialised incinerators		Process control						

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EEM ID	Generic name	Generic description	Project type	Energy savings (kWh per annum)	GHG reduction potential (ton CO₂-equivalent)	Cost savings (R million)	Implementation cost (R million)	PP (years)	Incentives (R million)
156	Steam production efficiency		Supply-demand matching						
157	Variable speed drives on boiler fans		Supply-demand matching					1-3	
158	Recover steam vent from deaerators	Recover steam vent from deaerators for deaerator feed water heating in steam station if no steam is vented.	Heat recovery/CHP					1-3	
159	Optimisation to increase material slip.	Assist with optimisation of process post the recent material change.	Supply-demand matching						
160	Operating material change	Operating material at end of life. Opportunity to replace with more efficient materials.	Supply-demand matching	254 935 909	10 520		244	<1	242.2
161	Waste heat recovery on power generation	The waste heat recovered from the power generation is used to produce steam.	New technology	169 396 157	112 211		537	<3	160.93

F. APPENDIX F: Case study questionnaire (Chapter 3)

Appendix F contains additional information related to Section 3.3. Appendix F.1 shows a summary of questionnaire respondents' highest qualifications and years of experience in the energy management field. Appendix F.2 shows the adapted questionnaire used to weight the complexity and prioritisation criteria.

Appendix F.1:

- A summary of the qualifications and years of energy management experience of the questionnaire respondents (Section 3.3).

Appendix F.2:

- Adapted questionnaire used by the respondents to weight criteria (Section 3.3).

Appendix F.1: Respondent details

A total of 22 respondents completed the questionnaire in Appendix F.2. The highest qualification and years of experience in the energy management field for each respondent are shown in Table F-1.

Table F-1: A summary of the questionnaire respondents' qualifications and years of experience.

Respondent	Highest qualification	Years of experience
1	PhD	7
2	PhD	8
3	PhD	9
4	PhD	7
5	PhD	26
6	PhD	2
7	PhD	8
8	PhD	10
9	PhD	17
10	PhD	5.5
11	Master's degree	5
12	PhD	15
13	PhD	6
14	PhD	6
15	PhD	14
16	PhD	5
17	Master's degree	2
18	Master's degree	3.5
19	Master's degree	5
20	PhD	4.5
21	PhD	15
22	PhD	4

Appendix F.2: Adapted questionnaire used in case study

The sample questionnaire provided in Appendix B.2 was adapted for use in the case study according to the availability of information on the suggested criteria. This appendix contains the adapted questionnaire used in the case study.

Prioritisation questionnaire

Goal of the questionnaire

The goal of the questionnaire is to assign weights to various energy efficiency measure (EEM) prioritisation criteria by pair-wise comparisons. The weighted criteria will then be used to prioritise competing industrial energy efficiency projects.

Background on the prioritisation method

The Analytical Hierarchy Process (AHP) was chosen as the prioritisation method. The AHP represents an accurate approach to quantifying the weights of decision criteria. The AHP method requires the problem to be modelled as a hierarchy. The participant compares each level of the hierarchy in a pair-wise manner. An example of the criteria hierarchy is provided in Figure F-1.

Participant requirements

The participant is requested to answer two questions. Question 1 requires the participant to disclose their highest academic qualification as well as years of experience in the energy management field. Question 2 requires the participant to compare prioritisation criteria and assigns weights according to the relative importance of one criterion over another. Question 2 is divided into three parts, namely Q2.1, Q2.2, and Q2.3.

Instructions for the completion of the questionnaire

1. Please answer Question 1 in the space provided.
2. Various project prioritisation criteria were researched and compiled into groups. Similar criteria were grouped into categories to form a hierarchy, as illustrated in Figure F-1. Each subquestion requires the participant to compare and score criteria from each group. Q2.1 and Q2.2 require the participant to compare and score technical and financial criteria, respectively. Q2.3 requires the participant to compare and score high-level criteria. Instructions for each question are provided at each question. Descriptions of the relevant criteria are provided at each question.

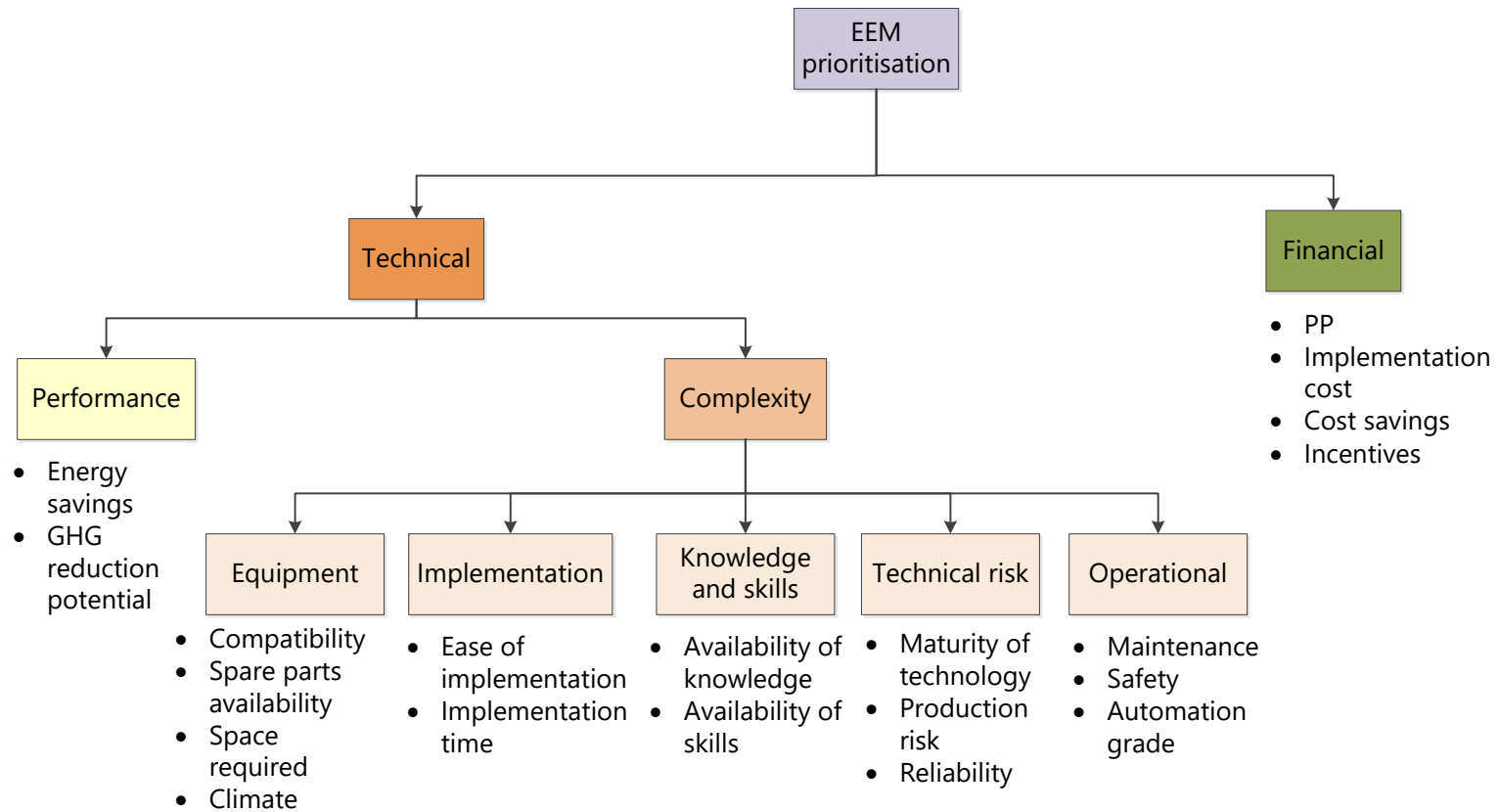


Figure F-1: The hierarchy of the prioritisation criteria used for the case study.

Question 1

1.1 What is your highest academic qualification? _____

1.2 How many years of experience in energy management do you have? _____

Question 2

Table F-2 is used to score the prioritisation criteria.

Table F-2: The scoring scale used to weight the prioritisation criteria.

Scoring scale	
Scale	Definition
1	Equally important
2	Equally or slightly more important
3	Slightly more important
4	Slightly to much more important
5	Much more important
6	Much to far more important
7	Far more important
8	Far more important to extremely more important
9	Extremely more important

Question 2.1: Technical criteria

1. Descriptions of the technical criteria are provided in Table F-3.
2. Complete each subsection of Table F-3 to Table F-11 by choosing the criterion that is more important.
3. Assign a score to the chosen criteria according to the scale in Table F-2.
4. Additional criteria that were not considered can be added to the allocated space at the end of the question.

Table F-3: Descriptions of the technical prioritisation criteria.

Group	Criterion	Description of criterion
Performance	Energy savings	The amount of energy in units of kWh that is saved by the implementation of the Energy Efficiency Measure (EEM).
	Greenhouse gas (GHG) reduction potential	The quantifiable reduction in CO ₂ -equivalent emissions because of the implementation of the EEM.
Complexity	-	All of the complexity factors described below in totality.
Equipment	Compatibility	The level of compatibility of the EEM to existing infrastructure.
	Spare parts availability	The availability of spare parts for preventative and corrective maintenance.
	Space required	An assessment of the availability of space for the implementation of the EEM. It includes the difficulty of the procurement of additional required land.
	Climate	The influence of the location climate on the technical performance of the EEM. For example, higher altitude levels can lead to an increased pressure drop over equipment.
Implementation	Ease of implementation	The level of technical and logistical difficulty in implementing the EEM.
	Implementation time	The time that it will take to fully implement the EEM.
Knowledge and skills	Availability of knowledge	The availability of local or in-house knowledge of the proposed EEM as well as the system that it will be implemented on.
	Availability of skills	The availability of existing or easily required skills for the implementation, operation, and maintenance of the proposed EEM.
Technical risk	Maturity of technology	The technology or EEM has been in use for a long time and most of its initial faults and inherent problems have been reduced or resolved. Mature technology usually has wide-spread use.

Group	Criterion	Description of criterion
	Production risk	The likelihood that the EEM will pose a risk to production quality or quantity as a result of disruption time or other factors.
	Reliability of technology	The capacity of the EEM to perform as designed; the resistance of the EEM to failure.
Operational	Maintenance	The level of maintenance that the EEM requires.
	Safety	The level of danger during the installation, operation, and maintenance of the EEM.
	Automation grade	The level of human input required for the operation of the EEM after implementation.

Table F-4: Pair-wise comparisons of the *Technical* criteria.

Technical criteria			
Criteria		Which criterion is more important?	By how much?
Performance	Complexity	Choose an item.	Choose an item.

Table F-5: Pair-wise comparisons of the *Performance* criteria.

Performance			
Criteria		Which criterion is more important?	By how much?
Energy savings	GHG reduction potential	Choose an item.	Choose an item.

Table F-6: Pair-wise comparisons of the *Complexity* criteria.

Complexity criteria			
Criteria		Which criterion is more important?	By how much?
Equipment	Implementation	Choose an item.	Choose an item.
Equipment	Knowledge and skills	Choose an item.	Choose an item.
Equipment	Technical risk	Choose an item.	Choose an item.

Complexity criteria			
Criteria		Which criterion is more important?	By how much?
Equipment	Operational	Choose an item.	Choose an item.
Implementation	Knowledge and skills	Choose an item.	Choose an item.
Implementation	Technical risk	Choose an item.	Choose an item.
Implementation	Operational	Choose an item.	Choose an item.
Knowledge and skills	Technical risk	Choose an item.	Choose an item.
Knowledge and skills	Operational	Choose an item.	Choose an item.
Technical risk	Operational	Choose an item.	Choose an item.

Table F-7: Pair-wise comparisons of the *Equipment* criteria.

Equipment			
Criteria		Which criterion is more important?	By how much?
Compatibility	Spare parts availability	Choose an item.	Choose an item.
Compatibility	Space required	Choose an item.	Choose an item.
Compatibility	Climate	Choose an item.	Choose an item.
Spare parts availability	Space required	Choose an item.	Choose an item.
Spare parts availability	Climate	Choose an item.	Choose an item.
Space required	Climate	Choose an item.	Choose an item.

Table F-8: Pair-wise comparisons of the *Implementation* complexity criteria.

Implementation complexity			
Criteria		Which criterion is more important?	By how much?
Ease of implementation	Implementation time	Choose an item.	Choose an item.

Table F-9: Pair-wise comparisons of the *Knowledge and skills* criteria.

Knowledge and skills			
Criteria		Which criterion is more important?	By how much?
Availability of knowledge	Availability of skills	Choose an item.	Choose an item.

Table F-10: Pair-wise comparisons of the *Technical risk* criteria.

Technical risk			
Criteria		Which criterion is more important?	By how much?
Maturity of technology	Production risk	Choose an item.	Choose an item.
Maturity of technology	Reliability of technology	Choose an item.	Choose an item.
Production risk	Reliability of technology	Choose an item.	Choose an item.

Table F-11: Pair-wise comparisons of the *Operational* criteria.

Operational			
Criteria		Which criterion is more important?	By how much?
Maintenance	Safety	Choose an item.	Choose an item.
Maintenance	Automation grade	Choose an item.	Choose an item.
Safety	Automation grade	Choose an item.	Choose an item.

Optional: Additional criteria not considered: _____

Question 2.2: Financial criteria

1. Descriptions of the financial criteria are provided in Table F-12.
2. Complete each subsection of Table F-13 by choosing the criterion that is more important.
3. Assign a score to the chosen criteria according to the scale in Table F-2.
4. Additional criteria that were not considered can be added to the allocated space at the end of the question.

Table F-12: Descriptions of the financial prioritisation criteria.

Criterion	Description of criterion
Payback Period (PP)	The amount of time it takes to recover the cost of the investment.
Implementation cost	The cost to implement the EEM, including capital cost and installation costs.
Cost savings	The monetary cost savings as a result of implementing the EEM, for example, reduced fuel demand leading to lower costs.
Incentives	The availability of qualifying incentives for the EEM such as tax incentives and government funding.

Table F-13: Pair-wise comparisons of the *Financial* criteria.

Financial criteria			
Criteria		Which criterion is more important?	By how much?
PP	Implementation cost	Choose an item.	Choose an item.
PP	Cost savings	Choose an item.	Choose an item.
PP	Incentives	Choose an item.	Choose an item.
Implementation cost	Cost savings	Choose an item.	Choose an item.
Implementation cost	Incentives	Choose an item.	Choose an item.
Cost savings	Incentives	Choose an item.	Choose an item.

Optional: Additional criteria not considered: _____

Question 2.3: High-level criteria

1. Complete each subsection by choosing the criterion that is more important.
2. Assign a score to the chosen criteria in Table F-14 according to the scale in Table F-2.

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3. Additional criteria that were not considered can be added to the allocated space at the end of the question.

Table F-14: Pair-wise comparison of the high-level prioritisation criteria.

High-level criteria			
Criteria		Which criterion is more important?	By how much?
Financial criteria	Technical criteria	Choose an item.	Choose an item.

Optional: Additional criteria not considered: _____

G. APPENDIX G: Phase 1 case study results (Chapter 3)

This Appendix contains additional results for the case study as a result of applying Phase 1 of the structured approach. Appendix G.1 contains the aggregated judgment matrices for the weighting of the complexity criteria via questionnaire (Section 3.3.1). Appendix G.2 shows complexity scores assigned to the Stage 2 EEMs (Section 3.3.1). Appendix G.3 shows the final normalised complexity scores, the assigned complexity level, and the method of verification (MOV) available for each Stage 2 EEM (Section 3.3.1).

Appendix G.1:

- Aggregated judgment matrices for the complexity criteria (Section 3.3.1).

Appendix G.2:

- Complexity scores assigned to each Stage 2 EEMs based on available project information (Section 3.3.1).

Appendix G.3:

- Final normalised complexity scores, assigned complexity levels, and the MOV for each Stage 2 EEM (Section 3.3.1).

Appendix G.1: Aggregated judgmental matrices for Complexity criteria

The complexity criteria were weighted by 22 respondents via questionnaire. The resulting aggregated judgment matrices for the pair-wise comparisons of the complexity criteria are shown in Table G-1 to Table G-6.

Table G-1: The aggregated judgment matrix for the *Complexity* criteria.

	Equipment	Implementation	Knowledge and skills	Technical risk	Operational	CR
Equipment	1.00	1.06	0.36	0.24	0.31	
Implementation	0.94	1.00	0.36	0.24	0.31	
Knowledge and skills	2.80	2.75	1.00	0.48	0.72	0.004
Technical risk	4.19	4.23	2.10	1.00	1.09	
Operational	3.28	3.26	1.39	0.92	1.00	

Table G-2: The aggregated judgment matrix for the *Equipment* criteria.

	Compatibility	Spare parts availability	Space	Climate	CR
Compatibility	1.00	1.06	0.36	0.24	
Spare parts availability	0.94	1.00	0.36	0.24	0.017
Space	2.80	2.75	1.00	0.48	
Climate	4.19	4.23	2.10	1.00	

Table G-3: The aggregated judgment matrix for the *Implementation* criteria.

	Ease of implementation	Implementation time	CR
Ease of implementation	1.00	0.50	
Implementation time	0.50	1.00	0.000

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Table G-4: The aggregated judgment matrix for the *Knowledge and skills* criteria.

	Availability of knowledge	Availability of skills	CR
Availability of knowledge	1.00	1.09	0.000
Availability of skills	0.92	1.00	

Table G-5: The aggregated judgment matrix for the *Technical risk* criteria.

	Maturity of technology	Production risk	Reliability	CR
Maturity of technology	1.00	1.06	0.36	0.017
Production risk	0.94	1.00	0.36	
Reliability	2.80	2.75	1.00	

Table G-6: The aggregated judgment matrix for the *Operational* criteria.

	Maintenance	Safety	Automation grade	CR
Maintenance	1.00	0.18	1.73	0.034
Safety	5.62	1.00	5.34	
Automation grade	0.58	.19	1.00	

Appendix G.2: Complexity scores assigned to case study

The complexity of the Stage 2 EEMs was evaluated by assigning a complexity score between 1 and 3 for each EEM with respect to each criterion. The assigned scores are shown in Table G-7.

Table G-7: The assigned complexity scores to the Stage 2 EEMs.

EEM ID	Compatibility	Spare parts availability	Space required	Climate	Ease of implementation	Implementation time	Availability of knowledge	Availability of skills	Maturity of technology	Production risk	Reliability	Maintenance	Safety	Automation grade
8	1	2	2	3	1	1	2	2	3	2	3	2	2	3
27	2	3	3	3	1	1	2	2	3	3	3	2	2	3
30	3	3	3	3	2	2	2	3	2	3	3	3	3	3
31	3	3	3	3	2	3	2	2	2	2	3	3	3	3
36	2	3	3	3	1	1	2	2	3	3	2	2	3	3
37	1	3	3	3	1	1	2	3	3	3	3	2	3	2
44	2	3	3	3	2	2	2	2	3	3	3	2	3	3
46	1	3	2	3	1	1	2	1	2	2	3	2	2	2
50	3	2	3	3	2	3	2	3	3	2	3	3	3	3
51	3	3	3	3	3	3	3	3	3	3	1	3	3	3
58	3	3	3	3	3	3	2	3	3	3	3	3	3	3
62	3	3	3	3	2	3	2	3	3	3	3	3	3	3
76	3	3	3	3	2	2	3	3	2	3	2	2	3	3
77	2	3	3	3	2	2	2	2	2	3	2	2	3	3
79	3	3	3	3	2	2	3	2	3	3	3	1	3	3
89	3	3	3	3	2	3	2	3	3	3	3	3	3	3
97	2	3	3	3	2	2	2	3	3	3	2	2	3	3
98	2	3	3	3	2	2	2	2	2	3	2	2	3	3
99	2	3	3	3	2	3	3	2	2	2	2	2	2	2
100	3	2	3	3	1	1	2	2	2	2	2	2	3	3
102	2	3	3	3	2	2	2	2	3	2	3	2	2	2
104	2	3	3	3	2	2	2	2	3	2	3	2	3	3

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EEM ID	Compatibility	Spare parts availability	Space required	Climate	Ease of implementation	Implementation time	Availability of knowledge	Availability of skills	Maturity of technology	Production risk	Reliability	Maintenance	Safety	Automation grade
111	3	3	3	3	2	2	2	3	3	3	3	2	3	3
115	2	3	3	3	3	3	2	2	3	2	3	2	3	3
117	2	3	3	3	2	3	2	2	3	3	2	2	3	3
118	2	3	3	3	2	3	2	2	2	3	2	2	3	3
119	2	3	3	3	1	3	2	2	2	3	2	3	3	3
120	2	3	3	3	1	3	2	2	2	2	1	2	3	3
121	3	3	3	3	3	3	2	2	3	2	2	1	3	3
122	3	3	3	3	2	2	2	3	3	3	2	1	3	3
123	3	3	3	3	2	2	2	3	3	3	3	3	3	3
124	2	3	3	3	2	2	2	2	3	3	2	2	3	3
125	2	3	3	3	2	2	2	2	3	2	2	2	3	3
126	2	3	3	3	1	1	2	2	3	3	3	2	3	3
127	2	3	3	3	1	1	2	3	3	3	3	2	3	3
128	1	3	3	3	2	2	2	2	2	2	2	2	3	3
129	2	3	3	3	1	1	2	2	3	2	2	2	3	3
130	1	3	3	3	1	1	2	2	3	3	2	1	3	3
131	3	3	3	3	2	1	2	3	3	3	2	2	3	3
132	2	3	3	3	1	3	2	2	3	3	2	2	3	3
134	2	3	3	3	1	2	2	3	3	3	2	2	3	3
147	1	3	3	3	1	1	2	1	1	2	2	2	3	2
160	3	3	3	3	2	3	2	3	2	2	3	3	3	3
161	1	2	2	3	1	1	1	2	3	2	2	3	2	2

Appendix G.3: Complexity levels assigned to case study

The final normalised complexity score for each Stage 2 EEM was calculated from the individual complexity scores relative to each criterion shown in Table G-7. Based on the final normalised complexity, a complexity level was assigned to each Stage 2 EEM. The final complexity score, complexity level, and available MOV for each EEM are shown in Table G-8.

Table G-8: Final complexity scores, complexity levels, and MOV for the Stage 2 EEMs.

EEM ID	Normalised complexity score	Complexity level	Verification method
8	0.019	High	Simulation; supplier performance results
27	0.021	Medium	Simulation
30	0.025	Low	Equipment check
31	0.023	Medium	Supplier performance guarantee; detailed calculations
36	0.022	Medium	None
37	0.023	Medium	Equipment check; simulation
44	0.024	Low	Simulation; detailed calculations
46	0.017	High	Simulation; expert knowledge; supplier performance guarantees
50	0.024	Low	Supplier performance results
51	0.026	Low	Supplier performance results; literature
58	0.027	Low	Similar previously implemented project
62	0.026	Low	Pilot
76	0.025	Low	Simulation; detailed calculations; expert knowledge
77	0.023	Medium	None
79	0.025	Low	None
89	0.026	Low	Supply-demand matching; test run
97	0.024	Low	Simulation
98	0.023	Medium	Simulation; detailed calculations
99	0.021	Medium	Simulation; supply-demand matching
100	0.020	High	Simulation; detailed calculations
102	0.020	High	Simulation; supply-demand matching
104	0.022	Medium	Simulation; supply-demand matching

EEM ID	Normalised complexity score	Complexity level	Verification method
111	0.025	Low	Simulation; supply-demand matching
115	0.023	Medium	Test run; detailed calculations
117	0.024	Low	Test run; simulation
118	0.023	Low	Test run; detailed calculations
119	0.023	Medium	Test run; detailed calculations
120	0.020	High	Simulation; test run; detailed calculations
121	0.022	Medium	Simulation
122	0.024	Low	None
123	0.026	Low	Equipment check; simulation
124	0.023	Medium	Equipment check; detailed calculations
125	0.021	Medium	Test run; detailed calculations
126	0.023	Medium	Equipment check; detailed calculations
127	0.024	Low	Simulation; supply-demand matching
128	0.021	Medium	Equipment check; detailed calculations
129	0.020	High	Simulation; detailed calculation
130	0.021	Medium	None
131	0.024	Low	Test run; supply-demand matching
132	0.023	Medium	Equipment check; detailed calculations
134	0.024	Low	Equipment check; detailed calculations
147	0.018	High	Simulation; detailed calculations; supply-demand matching
160	0.024	Low	Detailed calculations; supplier guarantees
161	0.017	High	Supplier guarantees; simulation; proof of performance
Total	1.000		

H. APPENDIX H: Phase 2 case study results (Chapter 3)

This Appendix contains additional results for the case study as a result of applying Phase 2 of the structured approach. Appendix H.1 contains the aggregated judgment matrices for the weighting of the prioritisation criteria via questionnaire (Section 3.3.2). Appendix H.2 contains the normalised scores of each prioritisation criterion relative to each Stage 2 energy efficiency measure (EEM) (Section 3.3.2).

Appendix H.1:

- Aggregated judgment matrices for the prioritisation criteria (Section 3.3.2).

Appendix H.2:

- Normalised prioritisation scores assigned to each EEM for each prioritisation criterion as well as the final overall prioritisation score of each EEM (Section 3.3.2).

Appendix H.1: Aggregated judgment matrices for prioritisation criteria

The prioritisation criteria were weighted by 22 respondents via questionnaire. The resulting aggregated judgment matrices for the pair-wise comparisons of the prioritisation criteria are shown in Table H-1 to Table H-4. The judgmental matrices for the weighting of the complexity criteria are shown in Table G-1 to Table G-6 in Appendix G.

Table H-1: The aggregated judgmental matrix for the high-level criteria.

	Technical	Financial	CR
Technical	1.00	0.40	0.000
Financial	2.52	1.00	

Table H-2: The aggregated judgmental matrix for the *Technical* criteria.

	Performance	Complexity	CR
Performance	1.00	3.17	0.000
Complexity	0.32	1.00	

Table H-3: The aggregated judgmental matrix for the *Performance* criteria.

	Energy savings	GHG reduction potential	CR
Energy savings	1.00	1.33	0.000
GHG reduction potential	0.75	1.00	

Table H-4: The aggregated judgmental matrix for the *Financial* criteria.

	Implementation cost	PP	Cost savings	Incentives	CR
Implementation cost	1.00	0.30	0.39	1.51	0.012
PP	3.32	1.00	1.80	3.89	
Cost savings	2.54	0.5	1.00	3.93	
Incentives	0.66	0.26	0.25	1.00	

Appendix H.2: Normalised prioritisation scores of case study

The normalised score for each Phase 2 EEM relative to each prioritisation criterion was calculated from the project information in Table E-1 as well as the complexity scores assigned in Table G-7. A final prioritisation score was calculated for each Stage 2 EEM by summing the product of each normalised criterion score with its respective global criterion weight. Based on the final prioritisation score calculated, the implementation order of the Stage 2 EEMs was ranked. The results of the case study are shown in Table H-5.

Table H-5: The normalised prioritisation scores for each Phase 2 EEM.

EEM	Energy savings	GHG reduction potential	Compatibility	Spare parts availability	Space required	Climate	Ease of implementation	Implementation time	Availability of knowledge	Availability of skills	Maturity of technology	Production risk	Reliability	Maintenance	Safety	Automation grade	Implementation cost	Cost savings	Incentives	PP	Final score	Rank
8	0.08	0.10	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.03	0.02	0.03	0.02	0.02	0.02	0.00	0.22	0.08	0.01	8%	3
27	0.08	0.09	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.05	0.08	0.09	6%	6
30	0.01	0.01	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.03	0.03	0.03	0.02	0.02	0.03	0.04	0.01	0.04	3%	14
31	0.01	0.00	0.03	0.02	0.02	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.03	0.02	0.02	0.03	0.01	0.01	0.02	1%	17
46	0.12	0.00	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.03	0.02	0.02	0.02	0.00	0.33	0.12	0.02	11%	2
50	0.00	0.00	0.03	0.02	0.02	0.02	0.03	0.03	0.02	0.03	0.03	0.02	0.03	0.03	0.02	0.02	0.16	0.00	0.00	0.03	3%	13
51	0.00	0.00	0.03	0.02	0.02	0.02	0.04	0.03	0.03	0.03	0.03	0.03	0.01	0.03	0.02	0.02	0.16	0.00	0.00	0.02	2%	15
58	0.05	0.06	0.03	0.02	0.02	0.02	0.04	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.01	0.04	0.05	0.01	4%	12
89	0.00	0.00	0.03	0.02	0.02	0.02	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.06	0.01	0.00	0.01	2%	18
97	0.04	0.04	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.16	0.02	0.04	0.39	14%	1
99	0.04	0.04	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.07	0.04	0.08	6%	8
104	0.00	0.00	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.02	0.03	0.02	0.02	0.02	0.31	0.01	0.00	0.11	8%	5
111	0.03	0.04	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.01	0.03	0.06	3%	11
123	0.03	0.04	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.01	0.01	0.03	0.01	3%	16

EEM	Energy savings	GHG reduction potential	Compatibility	Spare parts availability	Space required	Climate	Ease of implementation	Implementation time	Availability of knowledge	Availability of skills	Maturity of technology	Production risk	Reliability	Maintenance	Safety	Automation grade	Implementation cost	Cost savings	Incentives	PP	Final score	Rank
127	0.04	0.05	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.00	0.08	0.04	0.01	5%	10
147	0.14	0.23	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.03	0.14	0.06	7%	4
160	0.20	0.02	0.03	0.02	0.02	0.02	0.03	0.03	0.02	0.03	0.02	0.02	0.03	0.03	0.02	0.02	0.00	0.01	0.20	0.01	7%	9
161	0.13	0.26	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.00	0.05	0.13	0.00	7%	7
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	100%	