MULTI CRITERIA DECISION MAKING FRAMEWORKS TO AID SELECTION OF: DEMAND ASSESSMENT METHODS; LOW AND ZERO CARBON TECHNOLOGY ASSESSMENT METHODS; AND MODELLING TOOLS; FOR COMMUNITY ENERGY SYSTEM DEVELOPMENT.

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Multi Criteria Decision Making Frameworks to Aid Selection of: Demand Assessment Methods; Low and Zero Carbon Technology Assessment Methods; and Modelling Tools; for Community Energy System Development

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Dedication

For all my friends and family who helped me along the way, and especially for Karolina who convinced me to keep going.

Declaration of Authenticity and Author's Rights

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Declaration of Contribution to Previously Published Work

The author of this thesis was joint first author in the paper entitled “A modelling tool selection process for planning of community scale energy systems including storage and demand side management” by A Lyden, R. Pepper and P. Tuohy (2018), from which Chapters 8 and 9 are taken. The author’s primary contribution to this paper was the development of the modelling tool selection framework.

Signed: Date: 21/04/2020

Abstract

At the concept design stage for a Community Energy System (CES), modelling is required to assess the best possible solution(s) to be taken forward to detailed design stage. This modelling requires inputs on energy demands and Low and Zero Carbon Technologies (LZCTs) to be considered. Several methods exist to generate these modelling inputs; however, these vary greatly and there is generally an ad-hoc rather than a formalised approach used to select the most appropriate to use for a given case study.

Modelling tool(s) must be selected to accept these inputs, carry out analyses, and support generation of outputs to inform the concept design stage for the CES. There are many modelling tools for use at concept design stage which vary in quality, capability, resource requirement and relevance; again, there is generally an ad-hoc rather than formalised approach used to select the most appropriate tools(s) to use for a given case study.

The gap targeted in this research is this lack of a well-defined process for selecting appropriate methods for planning or concept design stage modelling. The aim of this research is to address this gap through the application of formal Multi-Criteria-Decision-Making (MCDM) techniques.

The research question asked was whether formal MCDM techniques could be adapted to usefully address these gaps. The methodology followed was first to elaborate the gaps more fully, investigate formal (MCDM) methods to identify suitable candidates, then to propose and develop frameworks to inform selection of: (i) methods to be used to assess energy demands, (ii) methods to be used to assess appropriate LZCTs to be considered, and (iii) appropriate modelling tools to be used, for the concept design stage of a CES development. These frameworks were then tested through application to case studies and their effectiveness assessed.

First the current state of the art is reviewed in developing concept designs for Community or District Scale Energy Systems and the problem of method selection elaborated.

Next, the state of the art in MCDM techniques are reviewed including techniques for selecting appropriate MCDMs and two candidate MCDMs identified as having potential; these are: Simple Multi Attribute Rating Technique Exploiting Ranking (SMARTER); and,

Commercial off the Shelf Software Selection Process (COTSSSP). These 2 methods are then taken forward within the 'hypothesise - develop - test' research methodology.

A common framework was then developed based on SMARTER and COTSSSP for selection of: (i) methods to be used to assess energy demands and (ii) methods to be used to assess appropriate LZCTs to be considered. The developed framework employs selection criteria which are ranked, weighted, and scored according to the requirements of the case study, and also screens methods that do not meet minimum requirements. The framework was then demonstrated and evaluated by application to a case study and the findings discussed.

A second framework was developed for selection of Modelling Tools. Due to the differentiation provided by the high number of modelling tool attributes available to be considered the framework was based on COTSSSP only. To support the framework individual tool characteristics were categorised. Tools are scored based on technical capabilities, tools without essential capabilities eliminated, and cable tools considered. The framework was then applied to a case study, and the findings discussed.

The proposal that frameworks based on formal MCDM methods could usefully inform the methods used at concept design stage was found to be correct, the frameworks were found to provide an ordered and logical process that support selection of best available methods in contrast to current ad-hoc approaches. Application of the developed frameworks and wider consideration of the applicability of MCDM techniques in energy system development will contribute to the realisation of improved CESs and also inform the development of enhanced processes in this area in future.

The contribution of this work has been to demonstrate the applicability of formal MCDM methods. The frameworks developed are intended to be further adapted and refined through future applications.

Abbreviations

AC - Advanced Control

AHP - Analytical Hierarchy Process

AV - AVerage Solution

CA - Community Agent

CAES - Compressed Air Energy Storage

CES - Community Energy System

CS - Cold Storage model

DC - Demand curtailment

DECC - Department of Energy and Climate Change

COTSSSP - Commercial Off The Shelf Software Selection Process

DSM - Demand Side Management

EDAS - Evaluation based on Distance from Average Solution

EKiBaM - Extended Kinetic Battery Model

EPC - Energy Performance Certificate

ESRU - Energy Systems Research Unit

FB - Flow battery model

FO - Fixed Order control

HOMER - Hybrid Optimisation of Multiple Energy Resources

IRENA - International Renewable ENergy Agency

KiBaM - Kinetic Battery Model

LIDAR - LIght Detection And Ranging

LS - Load Shifting

LZCT - Low and Zero Carbon Technology

MACBETH - Measuring Attractiveness by a Categorical Based Evaluation Technique

MB - Moving Boundary model

MCDM - Multi Criteria Decision Making

MKiBaM - Modified Kinetic Battery Model

MO - Modulating Output control

NDA - Negative Distance from the Average solution

NIS -Negative Ideal Solution

NO - Non-modulating Output control

NPC - Net Present Cost

OO - Operational Optimisation control

PDA - Positive Distance from the Average Solution

PH - Pumped Hydro model

PHPP - Passivhaus Planning Package

PIS - Positive Ideal Solution

RdSAP - Reduced Data Standard Assessment Procedure

RESURL - Renewable Energy for Sustainable Rural Livelihoods

ROC - Rank Order Centroid

SAP - Standard Assessment Procedure

SBEM - Simplified Building Energy Model

SMART- Simple Multi Attribute Rating Technique

SMARTS - Simple Multi Attribute Rating Technique with Swings

SMARTER - Simple Multi Attribute Rating Technique Exploiting Ranks

SSM - Simple Storage Model

STS – Seasonal Thermal Storage model

TOPSIS - Technique for Order Preference by Similarity to an Ideal Solution

TRNSYS - Transient System Simulation Tool

UO - User-defined Order control

Tables

Contents

1. Chapter 1 - Introduction

1.1. Background

Energy systems worldwide are undergoing a transition towards sustainability driven by three primary goals: energy security, energy equity, and environmental sustainability [1]. One impact is increasing use of renewable energy through Community Energy Systems (CESs). These systems have been the subject of a range of research including technical analysis [2]–[6], socio-economic studies [7], [8], and environmental and institutional studies [9], [10] which identify important roles for such systems in the future.

CESs have been defined as those in which locally available renewable energy is made use of, the local population are the primary stakeholders, matters are voted for locally and most of the benefits are seen locally [11]. They are becoming ever-more relevant, and have been gaining popularity and support in policy in Europe and beyond. UK policy, for example, has a target of 8% of renewable capacity being provided by community and locally owned systems by 2020 [12], in Scotland there is a target of 2GW by 2030 [13] and in Germany they accounted for 22% of installed renewable energy capacity in 2012[14].

Once a community decides to develop a CES, a group or body will need to be set up (or it may be pre-existing, such as a community council) to guide and drive the project. This group will be hereafter referred to as a community agent (CA), and its members will be the decision-makers. The exact make-up of the CA will differ case-by-case, but is like likely to be made up of local stakeholders such as residents, landowners and business owners. This group will define the overall vision for the project, but there may be no expert knowledge in renewable energy.

It is essential to assess energy demands of a community so that demand supply matching and viability of a CES can be modelled. Ideally demand profiles should be annual, with at least hourly resolution [15]. There are many different methods available to perform these demand assessments; these differ greatly in quality and applicability, yet there are no defined way in which to select the most appropriate demand assessment(s) for a case study.

The modelling of a CES must also include high-quality inputs gained from methods which assess potentially suitable Low and Zero Carbon Technologies (LZCTs). Again, there are many different technologies available with many different methods available for assessing them which vary greatly in quality - yet there is no available framework for the selection of the most appropriate methods for assessing LZCTs to provide these inputs to modelling.

Finally, modelling must take place to assess the viability of a CES, using inputs from suitable demand and LZCT assessments. Again, there are a wide variety of potentially suitable tools of tools, which differ greatly in quality and applicability. The most suitable tool or combination of tools must be selected for the best possible modelling, yet there is no defined way of selecting this.

The gap targeted in this research is the lack of a well-defined process for selecting appropriate methods for assessing demands, assessing appropriate LZCTs, and selecting modelling tools to support planning or concept design stage modelling.

1.2. Overall aim, research question, research method and approach

The aim of this research is to address these gaps in selection of methods through application of formal Multi Criteria Decision Making (MCDM) techniques. The research question asked was whether formal MCDM techniques could be adapted to usefully address these gaps.

The overall research method used was to hypothesise that MCDM methods could indeed be adapted and usefully applied within appropriate frameworks, then to test this hypothesis by: developing frameworks for decision making based on MCDM techniques; applying them to case studies; analysing findings from these applications in order to draw a conclusions on the hypothesis.

The approach followed was to elaborate the gaps more fully, to investigate formal MCDM techniques and identify potentially suitable candidates for adaption, to propose and develop MCDM frameworks for selection of: (i) methods to be used to assess energy demands, (ii) methods to be used to assess appropriate LZCTs to be considered, and (iii) appropriate modelling tools to be used, for the concept design stage of a CES development.

Then to test these frameworks through application to case studies, analyse their effectiveness, and discuss and draw conclusions on the hypothesis.

The wider contribution of this work is the identification that such processes should be formalised and the identification and demonstration of the potential for MCDM techniques to be synthesised to provide a formalised framework. The frameworks developed here can be used as is or further adapted and improved by other expert practitioner teams, ultimately possibly informing industry standards; the frameworks and the methods themselves can also be adapted, evolved and developed by the research community (e.g. incorporation of uncertainty and robustness analysis).

1.3. Chapter outlines

The research method and approach are reflected in the chapter layout as described below.

1.3.1. Chapter 2 outline – Literature review into state of the art: Problems in Community Energy Systems planning level design methods, and potential for application of MCDM techniques as solutions.

In this chapter, a literature review is performed on community energy systems planning level design including demand assessment methods, LZCT assessment methods, and modelling tools, and a gap identified in the process used for method selection. Formal MCDM techniques are reviewed and their suitability assessed for method/tool selection.

1.3.2. Chapter 3 outline – Problem statement, research aims, context, methodology and scope

The questions addressed by this work are identified, as are research aims. The methodology used to achieve these aims is identified. This is: (i) a literature review to identify gaps in the selection of demand assessment methods, LZCT assessment methods, modelling tools, MCDM techniques and processes for selection of MCDM techniques; (ii) selection of MCDM techniques to develop frameworks for the selection of demand assessment methods, LZCT assessment methods, and modelling tools; and (iii) the developing and testing of frameworks to select demand assessment methods, LZCT assessment methods, and modelling tools. The scope, context and limitations of the work are discussed .

1.3.3. Chapter 4 outline – Selection of MCDM techniques to develop frameworks for selection of Demand and LZCT Assessment Methods and Modelling Tools for a Community Energy System

A process for the selection of the most suitable MCDM techniques for a given situation is applied, with potential MCDM techniques being reviewed and finally suitable MCDM techniques being selected to form the basis of the demand and LZCT assessment method and modelling tool selection frameworks.

1.3.4. Chapter 5 outline – MCDM frameworks for selection of Demand and LZCT Assessment Methods. Use of COTSSSP and SMARTER to develop frameworks to select Demand and LZCT Assessment Methods for Community Energy Systems

This chapter takes the MCDM techniques selected in Chapter 4 as the basis for the demand and LZCT assessment method selection frameworks and develops these. Criteria, a scoring system and scoring guidelines are developed for the selection of the most appropriate demand and LZCT assessment methods for CES analysis. The frameworks are defined via a series of step-wise tables with scoring guidelines and step-by-step instructions for their use.

1.3.5. Chapter 6 outline - Demonstration of COTSSSP/SMARTER MCDM Demand Assessment Method selection framework through application to a case study

The framework developed in Chapter 5 for the selection of demand assessment methods is demonstrated. Decision-makers and requirements of the decision-making process specific to the case study are defined; tables are populated with exemplar demand assessment methods; and all methods are scored. A recommendation for the most appropriate demand assessment methods for use in the case study is made.

1.3.6. *Chapter 7 outline - Demonstration of COTSSSP/SMARTER MCDM LZCT Assessment Method selection framework through application to a case study*

The framework developed in Chapter 5 for the selection of LZCT assessment methods is demonstrated. Decision-makers and the requirements of the decision-making process specific to the case study are defined; tables are populated with exemplar LZCT assessment methods; and all methods are scored. A recommendation for the most appropriate LZCT assessment method/combination of methods for use in the case study is made.

1.3.7. *Chapter 8 outline - An MCDM framework for selection of Modelling Tools. Use of COTSSSP to develop a framework to select Modelling Tools for Community Energy Systems*

This chapter takes the MCDM techniques selected in Chapter 4 as the basis for the tool selection framework and develops this. Criteria, a scoring system and scoring guidelines are developed for the selection of the most appropriate tool(s). The framework is defined via a series of step-wise tables with scoring guidelines and step-by-step instructions for their use.

1.3.8. *Chapter 9 outline - Demonstration of COTSSSP MCDM Modelling Tool selection framework through application to a case study*

The framework developed in chapter 8 for the selection of modelling tools for a CES is demonstrated. Requirements of the decision-making process and decision-makers for the case study are defined; tool capabilities are classified as “essential”, “desirable” or “not applicable” for the case study, and all tools scored. Finally, a set tools is identified for further investigation.

1.3.9. *Chapter 10 outline - Discussion*

Successes, failures, weaknesses and strengths of the frameworks for selection of demand and LZCT assessment methods and modelling tools are discussed and how they make a contribution to the field to be taken forward by both practitioners and the wider research community.

1.3.10. Chapter 11 outline - Conclusions

The work contained in this thesis is concisely summarised, key conclusions are drawn including recommendations for future work.

2. Chapter 2 - Literature Review into State of the Art: Problems in Community Energy Systems Planning Level Design Methods, and Potential for Application of MCDM Techniques as Solutions.

2.1. Chapter 2 introduction

In this chapter, a literature review is performed on CES planning level design including demand assessment methods, LZCT assessment methods, and modelling tools, and a gap identified in the generally ad-hoc process used for method selection. Formal MCDM techniques are reviewed and suitability assessed for potential application to address the problems with this ad-hoc process.

To effectively assess and analyse a potential CES, there is a need to select the most appropriate (i) demand assessment methods, (ii) LZCT assessment methods and (iii) modelling tools for CES analysis. This chapter reviews CESs, demand assessment methods, LZCT assessment methods, modelling tools, and selection techniques, and identifies a gap in the ad-hoc process used in method selection.

Next, a range of potentially suitable MCDM techniques that could potentially be used to form the basis of the formal frameworks to replace the ad-hoc process are reviewed, as are processes for the selection of MCDM techniques. Suitable MCDM techniques that could be applied to inform CES planning level design are identified.

The chapter is structured as follows:

- Review into CESs, demand assessment methods, LZCT assessment methods, modelling tools, and selection techniques, problem identification.
- Review of formal MCDM techniques with potential for applicability.
- Review of formal techniques for selecting the most appropriate MCDM technique(s)

During the course of this PhD research, the author conducted site visits, spending time investigating various CES projects, learning and utilising a range of different methods and tools for their analysis. As part of this learning, the author took part in in-depth training, such as attending a 2-week PhD school for EnergyPlan – a tool developed by researchers at Aalborg University and used for national, regional and community scale energy system planning.

The CESs analysed during the conduct of this research included those on the Isle of Eigg, Findhorn and West Whitlawburn, and potential sites for CESs in Kinlochleven and various remote farming settlements in rural Sao Paulo state, Brazil. The methods and tools used to analyse the CESs ranged from questionnaires which the author developed in conjunction with social scientists, to energy systems analysis tools which perform energy balances using an hourly time-step.

During conduct of this research, work was presented as part of an International Energy Agency Annex (ECES Annex31: Energy Storage in Low Carbon Buildings and Districts), and piloted as part of a University Insight Institute project ("A Bridge Over Troubled Waters" [16]) and an EPSRC IAA project ("Major Tom to Ground Control: new integrated assessment for local renewable energy" [17]); outcomes from the latter were presented at the 23rd International Sustainable Development Research Society Conference, Bogota, Jun 2018 ("Sustainable renewable energy: towards the energy autonomy of rural communities in developing countries" [18]). Work undertaken as part of this thesis was published as a paper entitled "A modelling tool selection process for planning of community scale energy systems including storage and demand side management", published in a special edition associated with the IEA Annex 31 of Sustainable Cities and Society [19] and included in the Annex final report [20]. A second paper, "MCDM methods for selecting demand and LZCT options in Community Energy System planning level modelling" is in process with Sustainable Cities and Society.

Colleagues who shared their expert knowledge include ESRU colleagues (Andrew Lyden, Paul Tuohy); University of Strathclyde Business School (Brian Garvey, Mike Danson, Catalina Silva Plata); Aalborg University (EnergyPlan PhD School, IEA/CLIMA Workshop) (Henrik Lund, David Connolly, Poul Alberg Østergaard); CARES Consultant (Iona Hodge); Eigg Development Trust/Eigg Electric (Maggie Fyffe, John Booth); Kinlochleven Development Trust (Marion Smith); IEA Annex 31 (Fariborz Haghigat, Behrang Talebi, Claudio Del Pero, Gilles Fraise et al. [20]).

This experience gained during the course of four years of PhD research, participating in the above activities, using of a wide range of methods and tools to analyse a variety of differing CESs, collaborating and learning from colleagues, publishing and gaining feedback for work conducted, providing support for masters students modelling CESs etc. meant that the author was able to conduct a focussed and apposite literature review into these methods and tools, and the techniques for their selection.

2.2. Community Energy System Assessment, Overall Process

To aid CES development, there are many guides available e.g. [21]–[31]. These guides may include guidelines on e.g. group formation, community involvement, information on a range of Low and Zero Carbon Technologies (LZCTs), suitability checklists, schemes/grants available, tips for project development/installation with links to available bodies and resources, grid connection information, environmental considerations and case studies. For example, in the Scottish context, the Community and Renewable Energy Scheme (CARES) provided by Local Energy Scotland is a comprehensive set of resources [32]–[35]. To develop the CES further after consulting such guides, the CA will usually at some point employ the services of an expert e.g. a consultant to provide assistance. This is because technical capacity is often lacking in a CA [36]. Government agencies often allocate an expert to guide project development and community engagement. For example, after consulting the CARES guides, a CA will be assigned a project officer by Local Energy Scotland who will perform basic checks to the viability of the CES before recommending an expert (personal correspondence with Local Energy Scotland). Experts will employ technical methods to assess energy demands and LZCTs (discussed in greater depth in sections 2.3 and 2.4, respectively), and will model potential CESs using tools (discussed in greater detail in section 2.5).

While these guides and methods generally give good basic advice on suitability of individual technology options, they do not give a joined-up approach for effective integration of the overall local energy system including transport, heating and cooling, storage and demand side management (DSM), wider grid participation and control options. This integration of the overall energy system is addressed in a wide range of integrated energy system modelling tools [19], [37], [38] etc. but these typically require expertise beyond that available to the expert assigned or procured in current processes. It is generally accepted that to perform an adequate assessment, modelling tools are required to carry out an energy balance at hourly or sub-hourly time periods [39]. While these community scale energy system modelling tools exist, it is necessary to identify the appropriate tool for the specific situation; this in turn requires initial investigation of the current situation and the future options that should be modelled. The available community scale modelling tools have varying levels of user support and guidance on application and required input data (as reviewed in [19]), but generally require the user to pre-determine the energy demand data and also the range of suitable LZCTs to be considered.

These energy system modelling tools and associated approaches each have a limited scope; very few of the available tools and methods in the energy domain fully comprehend the wider socio-economic and environmental aspects of energy system transformation which will be main determinants of its impact [19].

Significant impacts such as effects of direct and indirect land use change, or wider socio-economic issues such as job creation, are generally not included in energy modelling tools, but rather covered in separate social and environmental impact assessments. Attempts have been made to capture this broader process in a single framework e.g. the “Renewable Energy for Sustainable Rural Livelihoods” (RESURL, [40]–[42]) project, which uses a multi-criteria decision making (MCDM) approach incorporating five “capitals” defined by the sustainable livelihoods approach, weighted based on community priorities. A range of technically feasible solutions is found through modelling, and the one with the highest overall benefit across all capitals selected.

A generic 10 step approach to definition and implementation of a CES for a given situation was synthesised from a review of the available literature and interviews with professionals within the community energy sector:

1. Current energy demand assessment: transport, heating and cooling, power, industry, others.
2. Current energy supply assessment: cross sector energy source and conversion processes.
3. Future energy demand assessment: anticipated changes in demands e.g. energy efficiency, fuel change, increases in population etc.

4. Appropriate future low and zero carbon technology option identification, including storage and DSM considering local contexts.
5. Current and “desired future” socio-economic and environmental situation assessment (including issues and opportunities e.g. fuel poverty, unemployment, skills).
6. Modelling tool(s) selection - energy, carbon, socio-economic, environmental.
7. Detailed input data gathering - energy, carbon, socio-economic, environmental.
8. Detailed scenario modelling - energy, carbon, socio-economic, environmental (normally individual or appropriate sub-combinations of LZCT options are evaluated, then promising combinations evaluated as long-term scenarios and as short term first steps).
9. Future option selection; long term roadmap and phased action plan creation. (Selection criteria to be used and methodologies to determine optimum solutions is an evolving area e.g. [43]).
10. Implementation, monitoring and refinement.

The overall process should ideally be carried out in the context of a multi-disciplinary team with strong local community representation and leadership to ensure an optimum solution is developed in synergy with wider socio-economic sustainability and environmental initiatives.

The work of this research is to address Steps 1-4 and 6 of the process in synergy with Step 7. It is intended to capture the energy system assessment and pre-modelling tasks normally carried out by a person with expertise in this domain, ideally as part of the wider team.

In order to understand the state of the art it is appropriate to review the current methods for energy demand assessment, LZCT assessment, CES modelling tools and selection techniques.

2.3. Community Energy System Demand Assessment Methods

Many methods are available that may be used in assessing energy demands, including: online tools based on measured or synthesised typical datasets; methods inferring from local physical survey data; public datasets giving high level measured data; methods which scale and manipulate synthesised typical low resolution (monthly, quarterly or annual) data to generate representative hourly demand profiles; and generic demand profiles which have been created from datasets. Some example methods for assessing heat, electrical and transport demands are given below.

Example heat demand assessment methods:

- An example of an online tool is the Scotland Heat Map, which shows annual heat demand KWh/m2 p.a.) on a 50m grid[44], [45] calculated using data from a variety of sources including: polygons from maps; building data including age and floor area; building data from Energy Performance Certificates (EPCs); and energy billing data.
- The Reduced Data Standard Assessment Procedure(RdSAP,[46] is a survey method for producing EPCs for existing dwellings simplified from the more detailed Standard Assessment Procedure (SAP, [46]) for new dwellings. The Simplified Building Energy Model (SBEM, [47]) provides a similar function for non-domestic buildings. SAP, RDSAP and SBEM produce monthly profiles for heating and domestic hot water based on "typical" user patterns; all are based on the EU standard monthly calculation method [48].
- The Passivhaus Planning Package (PHPP, [49]) is also based on the EU monthly method and used to determine if a building can be classed as "Passive House" – a designation for buildings which provide a high level of occupant comfort and energy efficiency which are almost entirely heated passively from e.g. solar gains or occupant radiated heat.
- There are several community scale energy system modelling tools which incorporate heat demand profile generation [19] e.g. Hybrid Optimisation of Multiple Energy Resources (HOMER, [50]) takes a monthly or annual demand and uses this to scale generic profiles for a household or community with the addition of diversity and other factors to create an annual demand with hourly resolution.
- Libraries of generic profiles are available e.g. the University of Strathclyde's Energy Systems Research Unit (ESRU) [51] provides measured data from a range of building types including residential buildings, schools and offices, that can be downloaded freely at [52]. These can then be further combined and manipulated using standard spreadsheet tools such as Microsoft Excel [53]. It is important to consider diversity in combining demand profiles to avoid over specification [54]. For

district heating planning diversity information is often made available or standards have been developed e.g. [55].

- Building energy simulation modelling tools such as ESP-r [56], [57], Transient System Simulation tool (TRNSYS, [58]), EnergyPlus [59] etc. require extremely detailed inputs at a building and material level to perform heat transfer calculations between nodes in a building model at sub-hourly timesteps to generate simulated performance and heat and hot water energy demand profiles. The requirement for very detailed input data means that such tools may be scoped out for community scale but they are increasingly used within higher level software constructs to address this limitation [60].
- Direct measurements from e.g. building monitoring equipment or bill data, may be available for defined periods for the system being investigated. Methods can be applied to normalise or extend these datasets either through manual manipulation of existing hourly datasets to better align to measurement data, or the use of embedded profile generators in some of the modelling tools [1].

Example electrical demand assessment methods:

- Libraries of generic profiles are available, such as the ESRU library [51], or provided by industry-standards organisations such as the UK ELEXON [61] with profile classes and instructions on their use in combinations to create a representative community electricity demand profiles. Diversity is an important consideration as for the heat demands, diversity factors to be applied to peak demands are generally available e.g. for the UK context [54].
- Richardson et. al. [62], developed an Excel-based tool which generates demand profiles based on user behaviour, appliance use, building occupancy etc. This particular tool (available freely at [63]) provides demand resolution of 1 minute in a bid to capture peak demand, and was validated using data from a number of residential dwellings. The model includes the influence of diversity. The work of Flett [64] builds further on this approach.
- SAP, RDSAP, SBEM and PHPP incorporate monthly electricity demand profiles as part of their energy balance calculations which can be extracted as representative of typical building demand profiles; PHPP can be used to generate a building

specific electrical demand profile based on survey or design-based assessment of equipment and appliances etc.

- A number of community scale modelling tools e.g. HOMER, EnergyPRO, incorporate a demand profile generator for electrical demand, which has the same functionality as for heat demand described above.
- Direct measurements may be available for defined periods for the system being investigated. Methods exist which can normalise or extend these datasets as described for the heat case.

Example transport demand assessment methods:

- Domestic transport demand is often estimated through census data [65] to find vehicle ownership, with average mileage [66], fuel type [67] and fuel consumption [68] including pattern of use [69] being applied to find energy total demand.
- Non-domestic transport including public transport can be estimated in a similar way [70].
- Transport surveys can be carried out for defined periods and the results extrapolated across the period of interest [71].
- Datasets also exist with transport use profiles for different classes.

These examples illustrate the range of different methods. There is variance between depth of detail, output data resolution, required input data resolution and integrity, ease of use and required skill level and training to competently use the method.

It is therefore a challenge to select the most appropriate method in a particular situation; the best option may also be to use a combination of methods. A framework to select the most appropriate demand assessment method(s) for a CES is lacking and an area to which this research directs attention.

2.4. Community Energy System Low and Zero Carbon Technology Assessment Methods

As for energy demand assessment methods, it is essential to assess which LZCT options are appropriate so that future CES options can be modelled. Ideally supply profiles should be (multi-)annual with at least hourly resolution [1]. An appropriate mix of energy sources and LZCTs can potentially improve energy supply [72] e.g. lower output from hydro in drier summer months can be compensated with solar. There are many methods for assessing LZCTs (e.g. [33], [50], [73], [74]).

These methods fall into categories of: online tools which draw from datasets and LZCT technical specifications; methods for analysing LZCTs which require long-term on-site data to be gathered; tools which require detailed technical specifications and resource data as inputs to generate supply profiles; and community guides which are used at a basic level e.g. site identification and basic rules of thumb for feasibility. Below are examples of specific methods relevant to a Scottish context for wind energy applicability; note that wind is used here as an example, in any real case study, all possible LZCTs should be considered at initial stages.

- Renewables Ninja [73] is an online tool capable of providing an hourly supply profile based on location and technical specifications from a library of wind turbines. The dataset is based upon the authors' validation and correction of NASA's MERRA and MERRA 2 datasets [75].
- "Wind Resource Assessment: A Practical Guide to Developing a Wind Project" [76] is an in-depth guide to wind resource assessment, covering site selection, installation and operation of a wind resource monitoring programme, data quality control, validation and extrapolation and wind flow modelling. The method requires a team of experts to undertake the assessment using data gathered on-site.
- District or regional scale modelling tools such as EnergyPRO [77], EnergyPlan [78] and HOMER [79] can be used to assess energy options at district or regional scale [19]. Many of these modelling tools include an embedded supply profile generator. This is then used in combination with turbine technical specifications and industry standard calculations to generate an electricity supply profile.
- The "CARES Renewable Energy: Wind Module" [33] is a community guide which lays out the stages of a wind project development and the processes at each stage. A rough guide on how to develop project vision, seek advice, select a site, funding, construction etc. is presented. The guide is an overview and not for assessing wind

turbine feasibility, other than discounting sites with average annual wind speed of less than 6m/s at 45m hub height.

- Building-specific methods such as monthly calculation-based SAP, RDSAP, SBEM and PHPP, or more detailed simulation-based modelling tools such as ESP-r, TRNSYS etc. can be used to assess the potentials of building specific technologies.
- Local data gathering methods for planning wind exist such as anemometer and Light Detection and ranging (LIDAR) methods.

LZCTs such as wind turbine and solar technologies are mature and they have well-defined methods for assessing their viability and power output. Conversely, nascent and innovative technologies may have no standard way of being assessed, have little or only low-quality data available, and have few (if any) relevant projects from which to gain experience. For an optimal CES, all LZCTs must be considered at the initial stage and none should be discounted before being analysed by an appropriate technical expert.

The most appropriate method of assessment from those available must be selected to assess each LZCT. The above methods have variance in depth of detail, output data resolution, input data resolution and integrity, and ease of use. In addition, the most appropriate way to assess an LZCT may be to use a combination of methods. To aid in selection of appropriate methods, formal selection techniques can be employed. However, a framework to select the most appropriate LZCT assessment method(s) is lacking and this is the area to which this research directs attention.

2.5. Community Energy System Modelling Tools

Given the importance of CESs, wide variation in possible supply, storage control options, and different contexts such as climates and user expectations, there have been many efforts to provide modelling support for the planning process from a range of different perspectives. A general method for community energy planning is described in [80]; a key element identified is the use of modelling tools. Many tools have been developed and applied to a range of situations; the following is a brief overview of different types of tool and their applications.

EnergyPLAN [81] is a national and regional planning tool which has been used to model a 100% renewable energy future for Denmark [82] and for many other studies [83]. It is applicable at community scale, and was used to model the island of Mljet in Croatia [84] in a comparative study with H_2RES; an alternative tool designed for simulating the integration of renewables and hydrogen storage into island systems [85]. In this study, it was shown that both tools gave very similar results; H_2RES focus is technical while EnergyPLAN supports technical and economic analyses. Both tools are deterministic and use an hourly energy balance over a year to calculate energy generated, stored, rejected, consumed, exported, lost, and produced in excess, as well as percentage of energy consumed from renewable sources.

HOMER [79] is a community-scale modelling tool, originally developed to support design of off-grid community scale electrical energy systems but expanded to model grid connected and thermal systems. One example is modelling a hybrid solar-biomass system for a remote area in Pakistan [86]. This study used electricity demand, available solar and biomass resource, and costs to analyse the techno-economic viability of such a system. HOMER was used to optimise system size using an hourly energy balance and with minimum net present cost (NPC) as objective function.

Merit [87] is another community-scale modelling tool which models demands, supply and storage using an hourly energy balance and provides results showing demand/supply match and renewable and non-renewable supply. It has been used, e.g., to model a hybrid wind/solar system for a care home in Scotland [88]. Multiple systems were modelled, and those shown to satisfy demand all year round analysed. The tool provides technical analysis only with cost calculations being done outside of the tool.

TRNSYS [89] has a user-defined time step as small as 1 second. A comprehensive library of components is available. Systems are described in detail and the solver is dynamic which means that TRNSYS is usually a building-level simulation tool [56]; the number of components and parameters required for a community scale system could be complex requiring expert level of technical systems knowledge and complex calculations take considerable time. It has been used to model hybrid solar PV/thermal systems with thermal and electrical storage [90]. TRNSYS and similar building level simulation tools can be scaled up for use at community-scale.

The tools described above are a sample of those available and serve to illustrate different approaches. There is general agreement that hourly modelling timesteps (or less) are required to adequately model such systems [15]. Modelling tools are often first developed from a specific perspective e.g. hydrogen for H2RES, off-grid for HOMER, building systems for TRNSYS, and then adapted to support broader planning of community scale systems. How to choose between the plethora of different tools, particularly for planning of renewable energy systems where storage and DSM are to be considered, is a key challenge to be addressed in this work.

A number of reviewers have previously provided an overview of modelling tool capabilities specific to the effective integration of renewable energy. In general it was found that the prior work, although extremely useful foundation for this research did not: (i) address all storage and DSM options, (ii) provide a sufficiently detailed categorisation of the models used to represent storage and DSM, (iii) provide a structured tool selection process. The most relevant of these previous works are briefly described below.

Connolly et. al. [91] reviewed 37 modelling tools (narrowed down from 68) regarding their suitability for the integration of renewable energy into energy systems; the details on the storage technologies used in the tools are high level i.e. stating whether a tool is capable of modelling pumped hydroelectric, battery, compressed air and hydrogen storage. Thermal storage and DSM are not included in the provided tables; ‘thermal storage’ is mentioned for three of the tools in textual descriptions. The underlying models for electrical and thermal storages are not discussed in detail; such information can be useful to inform tool selection as some models can be more accurate than others [92], [93]. The authors provide the review to inform tool selection and the provided information is indeed useful in this regard but a formal selection process is not specified.

Van Beuzekom et. al. [94] considered 72 modelling tools to find those capable at city scale of modelling multi energy systems considering all relevant energy carriers (electricity, heating, cooling, transport etc.). They considered in detail 13 of the tools which were open source. Information regarding the tools was usefully tabulated including: available RES components, storage options, economic parameters, scale, availability, objective, modelling approach, time step, evaluation criteria, user friendliness and training requirement. The paper identified the different storage technologies included in the energy tools but did not give detail on the underlying models. While it was highlighted that grid balancing is essential in districts utilising stochastic energy sources, the DSM and grid support modelling capability of the tools was not captured. No tool selection process was specified.

Allegrini et. al. [95] reviewed 20 modelling tools chosen based on their ability to "simulate and analyse urban energy systems". Storage discussion was limited to seasonal thermal storage modelling, with building level storage capability documented within the tables but not in detail, DSM also is not covered in detail.

Several further reviews of energy system modelling tools have been undertaken. Keirstead et. al. [37] reviewed 219 studies, examining areas of urban energy systems (technology design, building design, urban climate, systems design, policy assessment, land use and transportation modelling) to evaluate their potential for integrated urban design. Mendes et. al. [96] reviewed 6 bottom-up tools which focus on optimisation of community energy systems, finding DER-CAM and MARKAL/TIMES to be the most appropriate. Markovic et. al. [97] documented the capabilities and inputs/outputs of 11 tools, a short paragraph on each was provided in terms of their energy, economic and environmental analysis capabilities. Mirakyan and De Guio [98] undertook a review of 12 tools to consider the methods available for integrated energy analysis for cities and territories. Whilst useful to the user requiring more information on a range of tools, these reviews all lack details on storage and DSM functionality and modelling, and none provide any tool selection process. Therefore, a framework to select the most appropriate CES modelling tool(s) is lacking and an area to which this research directs attention. To aid in selection of appropriate tool(s), formal selection techniques can potentially be employed.

2.6. Method Selection techniques

Based on discussions with a range of stakeholders (Note 1 at start of this section) and also from the reviews carried out of CES planning level design applications summarised in the previous section, selection of the most appropriate demand and LZCT assessment methods and modelling tools is usually an ad-hoc, informal task based on the available sources and skills, experience or biases of the expert carrying out the work. In principle, whilst the decision maker should select the method or tool which best fits the needs of the situation, they may also make a decision based on a variety of other factors such as available literature, cost, familiarity, support available, training requirements etc. [99].

In the literature, and in discussion with available experts, no formalised way of selecting the most appropriate methods or modelling tools for energy system analysis was found. There are, however, formalised techniques to aid selection in general that are applied in other domains. These generally define an aim for the decision-making process and criteria to score options against satisfying this aim. Criteria are weighted with respect to their importance, with options being scored based on performance on the criteria; a decision can then be made. This approach is labelled Multi Criteria Decision Making (MCDM) [100]. Some MCDM techniques such as Simple Multi Attribute Rating Technique Exploiting Ranks (SMARTER) simplify this process by requiring decision-makers to sort criteria in order of importance to assign criteria weights [101]. Analytical Hierarchy Process (AHP) further simplifies this by asking the decision maker to make pairs of comparisons between criteria to assign weights and final scores to options [102]; there are however well-documented problems with this technique [103]. COTSSSP [104], [105] is another MCDM technique which asks the decision maker to categorise criteria as “essential”, “desirable” and “not essential”, with options incorporating all “essential” criteria then being judged on their “desirable” criteria.

Selection of an MCDM technique can itself be ad-hoc; often decision makers select those they have most experience in, or for which software is available [106]. As the authors of [107] state, “the choice of an appropriate (MCDM technique) is one of the most difficult problems to which the analyst is confronted in multicriteria decision aiding”. However, selection of the correct MCDM technique is essential as different techniques can yield different outputs with identical inputs[108]–[112]. Work such as [109], [113]–[115] has therefore been undertaken to establish processes to assist in the selection of the most appropriate MCDM technique for a given situation. However, as the authors of [107] state, the nature of questions asked in selecting an MCDM technique makes many such processes flawed; better to gradually narrow down the list of suitable techniques through a series of questions. Reports such as [100] and [115] adopt this approach.

Once a suitable MCDM technique is found, it could in principle be usefully employed to aid a decision maker in the selection of the most appropriate energy demand and LZCT assessment methods for a CES study. Selection of an appropriate technique is then one of the items to be addressed here.

2.7. Review of MCDM techniques

In CES analysis, a finite number of method(s) and tool(s) should be judged, with the most appropriate method(s) and tool(s) being taken forward for use in modelling. The achievement of this will be based on measurable criteria e.g. the inclusion of parameters including cost/kWh energy produced, grid independence, CO2 produced per kWh, timestep, job creation etc. Weighting of these criteria based upon community priorities is also likely.

This is the general definition of Multi Criteria Decision Making MCDM [100], [116]. MCDM is also known as Multi Criteria Analysis, Multi Criteria Decision Analysis and Multi Attribute Decision analysis; for clarity MCDM shall be the terminology taken forward in this work. Multi Objective Decision Making (MODM) is another approach used to describe techniques which begin with multiple objectives, defining constraints to define an "ideal" option [117]. As the work of this thesis will focus on selection rather than design of options, MODM will not be considered. MCDM techniques are increasingly being used in renewable energy developments due to their ability to handle complex decisions with several criteria spanning environmental, social, technological, practical and economic aspects [118]. They combine these aspects and simplify the decision making process in a transparent way to provide more consistent results. As the requirements of the selection frameworks exactly match the definition of MCDM, the search for selection techniques is restricted to this particular field.

There is a common misconception that MCDM techniques, if used properly, will provide the analyst with the best option [116]. This is not the case as MCDM techniques do not perform an optimisation; rather MCDM techniques provide a decision-making framework for the analyst to consider options and judge them based on multiple criteria in an ordered and consistent way, such that they will be able to feel confident about making a decision. There is also a myth that MCDM takes the subjectivity out of a decision making process; again this is not the case. Rather MCDM techniques make this subjectivity explicit and transparent. MCDM techniques are ideally to be used such that the decision makers will explore the problem at hand in more depth and be able to understand priorities and objectives of their decision making process in a meaningful way. MCDM is intended to aid the decision maker rather than act as a substitute for them [116] .

MCDM techniques have been defined by Belton and Stewart [116] to fall generally into one of three categories:

- "Value measurement models" score options numerically such that the score represents the level of preference one option has over another

- “Goal, aspiration or reference level models” define an acceptable level of performance for each criterion. Options are judged on each criterion and those which meet this threshold are then used to populate a subset of acceptable options for further consideration
- “Outranking models” compare each option on each criterion in a pairwise manner so that options can be ranked in order of their performance

“Value measurement models” follow the axioms set out in Multi Attribute Value Theory (MAVT) [119] and its successor Multi Attribute Utility Theory (MAUT) [119], [120] . MAVT follows a simple linear additive model under conditions of certainty; a finite set of options are scored based on their performance on weighted criteria. A general objective of the decision making process is defined, and criteria are selected which will allow options to be judged in how well they fulfil the objective. Criteria are then given a weight according to their importance and to account for the difference in the magnitude of criteria scoring scales; usually these weights will sum to 1 or 100. MAVT assumes preferential independence between criteria i.e. that there is no form of interaction between criteria and that the performance of an option on one criterion is independent of its performance on another. The most basic way in which MAVT operates is if the decision maker, can at the very least, identify a weak order of preference i.e. is able to identify if an option scores better or worse than another option on a given criterion. Usually, however, problems are more complex than this and there are several options being scored on several criteria. In such cases, additive functions are used to create an overall additive performance score; each option is scored according to performance against each of the criteria, and an overall performance score is obtained from the sum of criteria scores multiplied by their weights. These options can then be ranked according to their overall scores – this should be done with caution, however, as scores and rankings can change upon performance of sensitivity analysis [121] .

MAUT expands this by providing an update which includes risk and uncertainty, and is “a more rigorous methodology for how to incorporate risk preferences and uncertainty into multi criteria decision support methods” [122]. MAUT assigns a utility value to each of the options under consideration, through the use of a multi attribute utility function, U. This function describes the preferences of the decision maker, capturing the score and the attitude to risk on each criterion, as well as the trade-offs between each criterion [123].

Utility Additive (UTA, [124], [125]) techniques are based on the axioms of MAUT in that an additive utility function is used. However, it operates on the premise that MAUT techniques do not model reality sufficiently as a decision maker will usually still compare all of the options "in their head" rather that compare their individual utility functions. UTA therefore provides a set of utility functions for each option, which capture the decision maker's preferences, and uses linear programming to assess these functions and ensure their consistency.

"Goal, aspiration or reference level models" tend to employ algorithms which aim to satisfy these goals as far as possible. These will contain two essential components; a description of the relative importance of criteria and an aggregation model which allows criteria to be compared.

"Outranking models" compare all options against each other on their performance on each individual criterion on a pair-wise basis. This assumes the decision maker can say, at the very least "Option A performs at least as well as option B on a given criterion". Preferences can also be estimated using a fuzzy function which incorporates the credibility of this statement; setting thresholds for this can, however, be problematic [126]. The next stage involves ordering the options based on these pair-wise comparisons, and can be aided through the use of tools such as a Pugh Matrix [127].

There is a wealth of different MCDM techniques falling into the above categories; rather than review them all with regards their applicability to a piece of research, it would seem prudent to first narrow the field by employing a process to select the most appropriate MCDM technique for the requirements of this research. The next section reviews such processes.

2.8. Review of processes to select the most appropriate MCDM technique

This section will review the range of differing processes available to select the most appropriate MCDM technique for a particular case study.

Different MCDM techniques can produce different results when applied to the same situation [108], [110], [128], [129] , and to obtain an acceptable solution to the case study, an appropriate MCDM technique needs to be selected [107]. Additionally, the selection of the most appropriate MCDM technique is widely accepted as one of the most difficult problems facing the decision maker in MCDM [106], [107], [116], [128], [130]. There have been several attempts to simplify the process which usually employ one of the following: treating the selection of an MCDM technique as an MCDM problem; asking questions of the decision maker to aid their selection; or documenting characteristics of MCDM techniques so that the decision maker has as much information as possible before making a decision.

For example, Wątróbski et. al. [106] review different processes for MCDM technique selection as well as 56 different MCDM techniques to present a generalised framework for MCDM technique selection, covering as many fields and techniques as possible. An online tool to aid decision makers in their selection is also presented [131]. The methodology essentially defines and categorises MCDM technique capabilities and asks the user if their particular problem requires these capabilities. Similarly, Velasquez and Hester [132] present a review of the most common MCDM techniques, and their advantages and disadvantages to give a guide as to which MCDM techniques should be used for a given situation. This is, however the weakness of these approaches; rather than being guides to selection, they act more as a documentation of capabilities, advantages and disadvantages. In this way, decision makers are assumed to know what particular capabilities are required from an MCDM approach. For example, one category asks the user if their problem requires weights, but there are no guidelines given on how to determine if this (or any other capability) is a requirement for the given situation. These studies are, however, useful in providing a clear source of information on available MCDM techniques.

A different approach is presented by Kurka and Blackwood [115], reviewing 6 studies in which an MCDM method was selected and documenting all criteria used in these studies. From this, the most relevant criteria to the selection of an MCDM for a renewable energy development were selected. These were: measures to deal with uncertainty; user-friendliness and flexibility; transparency and communication, and multi-stakeholder inclusion. MCDM techniques are then scored against these on a 3 point scale (low/medium/high), treating the MDCM selection itself as an MCDM problem. Their work was criticised for their limited range of application – often only the best-known MCDM techniques are considered, or an arbitrary field of application is chosen [106] . Ozernoy [130] also treats MCDM technique selection as an MCDM problem and resents a conceptual framework to select the most appropriate MCDM technique. The author states that, at a minimum, the following information is required to make a decision:

- Characteristics for evaluation of each situation
- List of all available MCDM techniques
- Objectives to be satisfied by the selected MCDM technique
- Differing characteristics of each MCDM technique

This is expanded further into a hierarchy of characteristics to evaluate the MCDM techniques available for a case study, based around: decision problem, decision maker and resource constraints; these form the criteria of the MCDM process to select the most appropriate MCDM technique.

Contrary to this, Guitouni and Martel [128] believe it is important to avoid the vicious circle of employing MCDM to select an MCDM technique and instead present seven tentative guidelines to aid in MCDM technique selection.

Likewise, Roy and Słowiński [107] state that whilst the selection of an MCDM technique is indeed an MCDM problem, due to the nature of the questions to be asked, it cannot be approached as such. Due to the complexity and variety of problems which MCDM techniques address, an MCDM-based MCDM technique selection process is not possible. Instead, they argue that selection of a technique is only effective if a series of questions are asked. Their work therefore presents a series of questions for a decision maker to ask in their selection of an MCDM technique. These questions begin high-level and become more specific so that the decision-maker can narrow down the applicable MCDM technique. Such a process effectively addresses the criticisms of other processes in this field, providing a sensible and transparent approach.

The Roy and Słowiński approach has been successfully used in several applications e.g. to select the PROMETHEE GDSS MCDM technique to calculate the preferences of decision-makers in the management of water resources in Brazil [133]; to select AHP to aid in designing the layout of port terminals [134]; to select AHP to aid in the design of railway terminals [135]; as the basis of a new framework to select MCDM techniques to select third party logistic providers [136]; to select the MACBETH MCDM technique to appraise regulatory policy options [137]; and to select a combination of AHP and Choquet Integral MCDM techniques to evaluate social housing initiatives [138]. Unlike other processes, the literature review uncovered no substantial criticism of the process; in addition, it was co-authored by Bernard Roy and Roman Słowiński - pre-eminent professors in the field of MCDM. It would therefore appear that this process is the most transparent and robust process to use in selecting MCDM techniques for a particular problem – although there were no examples of it being used in energy options appraisal.

2.9. Synergistic combinations of MCDM techniques

It is recognised that, due to the strengths and weaknesses of various MCDM techniques, it can be beneficial to combine them to create a synergistic technique. For example, in [139] MACBETH and EDAS are used in combination to evaluate between steam boiler alternatives for a dyehouse. In this work, MACBETH is used to determine the weights – as EDAS does not perform this function - and options are ranked using EDAS. In [140], AHP and fuzzy TOPSIS were combined to evaluate and select mobile health applications; AHP was used to determine criteria and sub-criteria weights, and fuzzy TOPSIS was used to rank the options. [141] studied the public and private impacts of LZCTs using a combination of TOPSIS, EDAS and the weighted aggregated sum product. This framework was applied to Lithuania to select the most appropriate LZCTs. [142] combined EDAS with Decision-Making Trial and Evaluation Laboratory (DEMATEL) to develop a life-cycle sustainability decision-support framework for hydrogen production technologies. This combination used DEMATEL to elicit the weights, a functionality which EDAS is lacking. Findings from the study were that the combination of techniques was effective and more robust than either technique in isolation. [143] used compensatory and non-compensatory techniques in combination; weighted summation was used with Electre II and Rank Order Centroid (ROC) weighting such that “The compensatory technique provides a sound measure of overall performance of a forestry system, whereas the non-compensatory technique alerts decision makers to presence of particularly poor performance with respect to individual criteria.”

It would appear that provided MCDM techniques are compatible and robust, they can be combined effectively to make up for shortcomings or lack of desired features; of note are techniques that do not weight options being combined with techniques that do, and non-compensatory and compensatory techniques being combined.

2.10. Chapter 2 conclusion

This chapter has reviewed CES assessment, CES demand assessment methods, LZCT assessment methods and modelling tools. It was found that whilst these methods and tools vary widely in depth, detail and required operator skill, there are no existing frameworks for the selection of the most appropriate methods and tools. Generally, MCDM techniques do exist for the evaluation of solutions for a problem, but there is no specific framework to aid in CES development. There does exist what appears to be a robust and transparent process for the selection of the most appropriate MCDM technique for a given situation, however no evidence of it being applied to energy options appraisals could be found within the literature.

3. Chapter 3 - Problem Statement, Research Aims, Context, Methodology and Scope

3.1. Problem statement, research aims, and context

From the literature review, and in the context of the generic 10 step approach to definition and implementation of a CES outlined in section 2.1, there are clear gaps in the assessment of energy demands and suitable LZCTs, and modelling tools for a CES. There are many methods for assessing demands and assessing suitability of LZCTs, and many tools for modelling a CES, with no formalised approach for selecting the most appropriate for a given situation.

The questions directly addressed in this work are (i) "how to select the most appropriate method(s) for assessing the current and future energy demands?" (ii) "how to select the most appropriate method(s) for analysing applicability of LZCTs?" and (iii) "how to select the most appropriate tool(s) for modelling a particular CES?". Answering these questions will correctly inform the assessment, modelling and implementation processes.

The aims of the work presented in this thesis, therefore, are to develop pre-modelling frameworks to support (i) method selection for energy demand assessment, (ii) method selection for LZCT applicability assessment and (iii) modelling tool selection. Frameworks (i) and (ii) will support the generation of appropriate modelling inputs for a CES study; framework (iii) will support modelling.

The context for the work of this thesis has included a number of related initiatives in Community Energy Systems; the PhD was initially funded to build further on the research outcomes from the EU FP7 ORIGIN (Orchestration of Renewable Integrated Generation in Neighbourhoods) project which had produced CES models for a number of EU Ecovillages and identified limitations in current methods and modelling tools; the PhD was carried out in the context of participation in the IEA ECES Annex 31 "Energy Storage In Low Carbon Buildings and Districts: Optimisation and Automation" including participation and presentation at workshops, contributing to the Annex report and publishing in an Annex special edition; practical experiences of CES planning level design methods were gathered through involvement with GCRF/ESRC/EPSRC IAA/University Insight projects in Eigg, Kinlochleven, Findhorn, West Whitlawburn and several rural communities in Brazil involving

Business, Community, Economics as well as Engineering experts; use of a range of modelling software and methods were investigated including training from experts; these included mentoring in the use of MERIT software by ESRU experts, a 2 week PhD school in Aalborg University on EnergyPlan, and on-line support in the use of a wide range of other tools and their application methods; current industry practice was explored through engagement with the Scottish Government CARES appointed CES Consultants and individuals running the Findhorn, Eigg, and West Whitlawburn CESs and planning the Kinlochleven CES.

3.2. Methodology

The overall research approach taken was to hypothesise that formal frameworks could be developed to usefully address the gaps, then develop and test such methods, before drawing conclusions and presenting outcomes. At each stage the work was progressed by identifying the state of the art through discussion with available experts and review of relevant literature, proposing, and then testing and refining through: discussion with expert users, testing through application, and further review of outcomes with expert users (the work in parts has been reviewed by experts and included in IEA ECES Annex 31 final report and also published in an Annex related special edition Journal paper). The specific methodological steps taken are outlined in the following sections:

3.2.1. State of the Art Assessment and Literature review (Chapter 2)

A state of the art assessment and literature review was performed to gain a solid background from which to develop the work. The assessment and review was informed by insights gained from interactions with a wide range of experts and practitioners, and experience gained from practical application of current methods and tools supported by these experts and practitioners (section 2.1). Chapter 2 reviews the state of the art in: (i) CES planning level design methods, (ii) demand assessment methods, (iii) LZCT assessment methods, (iv) modelling tools, (v) MCDM techniques and (vi) processes for selection of MCDM techniques. This review uncovered the gaps that are to be addressed in this research, and potential solutions to be built on and tested.

The literature review found that the methods and tools available for CES analysis vary widely in depth, detail and required operator skill. Despite the selection of the most appropriate methods and tools having a significant bearing on the quality of the results, there are no existing frameworks for the selection of the most appropriate methods and tools; generally their selection is ad hoc. To aid in this selection it was identified that MCDM techniques could be used effectively, but there is no specific framework to aid in CES development. A robust and transparent process for the selection of the most appropriate MCDM technique for a given situation was identified; however, no evidence of it being applied to CES demand assessment method, LZCT applicability assessment method or modelling tool selection was found within the literature.

3.2.2. Selection of MCDM techniques to develop frameworks for selection of demand and LZCT assessment methods and modelling tools for CES development

It was established in the literature review in Chapter 2 that MCDM techniques have been effectively used to aid selection in general. Several MCDM techniques were identified as potentially suitable for selecting the most appropriate demand and LZCT assessment methods and tools for CES analysis; it was proposed that a suitable technique or combination of techniques is selected from these. For this purpose an MCDM technique selection processes was proposed to select the most appropriate MCDM technique(s) for a given situation. From section 2.8 in the literature review, a technique defined by Roy and Słowiński [107] was identified as most suitable; it has already been used successfully in a multitude of engineering situations [133]–[138], and it was proposed in this research that it could be applied succesfully to the selection of MCDM techniques to develop frameworks for the selection of demand and LZCT assessment methods and tools for CES analysis.

The Roy and Słowiński technique was applied individually to the problems of selecting MCDM techniques for developing frameworks for the selection of (i) demand assessment methods, (ii) LZCT assessment methods and (iii) modelling tools for CES analysis. Each time the technique was applied, the specific context and requirements of each framework was considered, so that the most appropriate MCDM technique(s) was/are selected to form the basis of each framework. This work is presented in chapter 4 which identifies the methods to be used in frameworks that support the required decision making processes.

3.2.3. Development and testing of frameworks for selection of demand and LZCT assessment methods and modelling tools for CES development

Use of the Roy and Słowiński technique showed one or more MCDM techniques as the most suitable to form the basis of the demand and LZCT assessment methods and tool selection frameworks. There is good precedent of complementary MCDM techniques being combined to make up for each other's shortcomings [139], [141]–[143]; possible beneficial combinations available to form the frameworks, were explored. The frameworks were then developed using established rules laid out for the selected MCDM technique(s).

The developed frameworks were then applied to case studies with appropriate changes being made through iterative testing, and a final framework being arrived at for each of the required decisions. The outcomes from the applications were discussed.

The work undertaken in this thesis provides logical frameworks giving clarity to a previously ad-hoc process. The contribution is intended to sit within an overall CES development methodology such as outlined above in Section 2.2.

The contribution of this thesis is the demonstration of the useful application of formal MCDM based approaches to provide a more secure basis for CES planning level assessments rather than current ad-hoc methods, this is of increasing importance due to the proliferation of CES planning level assessments and the potential for sub-optimal designs based on poor selection methods.

The frameworks developed here are shown to have applicability and may be used and adapted further by practitioners, however the wider contribution is the process of application rather than the definitive contents of the frameworks which will be expected to be evolved or adapted in future based on further application and integration of further techniques from research such as uncertainty and robustness analysis etc.

3.3. Scope

The MCDM based frameworks developed and brought forward during this work are offered as a contribution to knowledge to be applied, adapted and further developed with the end goal of ultimately realising improved CESs. There have been significant interactions with researchers and practitioners in informing the criteria and scoring within the frameworks and while these are useful in current form they would be expected to go through further evolution and refinements before ultimately having the potential to inform industry standards. The methods themselves and their application will continue to evolve and it has not been possible within the scope of the work to address all of these potential developments; one area for future work that has been identified is the incorporation of calibration, uncertainty and robustness analysis in the overall approach to CES developments. The development of the frameworks to include these elements has been theorised as future work to build further on the outputs from this thesis.

4. Chapter 4 – Selection of MCDM Techniques to Develop Frameworks for Selection of Demand and LZCT Assessment Methods and Modelling Tools for a Community Energy System

4.1. Chapter 4 introduction

There is a need to formalise techniques for selecting the most appropriate (i) demand assessment methods, (ii) LZCT assessment methods (iii) modelling tools for CES analysis.

This aims of this chapter are to (i) select a process for the selection of MCDM techniques and (ii) use this process to select MCDM techniques to develop frameworks for the selection of demand and LZCT assessment methods and modelling tools.

The chapter is structured as follow:

- Selection of process to select MCDM technique(s) to develop frameworks for selection of demand assessment methods, LZCT assessment methods and modelling tools for a CES
- Selection of MCDM technique(s) to develop a framework for selection of demand assessment methods for a CES
- Selection of MCDM technique(s) to develop a framework for selection of low and zero carbon technology assessment methods for a CES
- Selection of MCDM technique to develop a framework for selection of modelling tools for a CES

4.2. Selection of process to select MCDM techniques to form basis of frameworks

The literature review in Chapter 2, Section 2.8 showed the process described by Roy and Słowiński [107] to be the most robust, sensible and transparent process for the selection of the most appropriate MCDM technique(s). Whilst it was not shown in the literature that the process had been used successfully in energy options appraisals, it had been used successfully in engineering applications; it is therefore sensible to believe that the process will be suitable. Showing the accuracy and robustness of the process in such situations is an additional aim of this research.

Therefore the 3-stage Roy and Słowiński [107] **MCDM technique selection process shall be used in this paper.**

The process is structured as follows:

Stage 1 asks the most high-level and important question for a decision-maker in the selection of an MCDM technique:

“Taking into account the context of the decision process, what type(s) of results the method is expected to bring, so as to allow elaboration of relevant answers to questions asked by the decision maker?”

There are then five possible types of results which MCDM techniques can output; these are:

1. Numerical value/score assigned to each option.
2. Ranking of options without scoring
3. A smaller subset of options is selected
4. Each option is assigned to one/multiple categories
5. A subset of options with “remarkable properties” is selected from a large set of options as an input to further decision making (this is a screening process).

There are several MCDM techniques which fall under each category; this will allow the selection of a set of techniques which can be narrowed down by asking a set of subsequent questions.

Stage 2 asks the following questions, in no particular order of preference:

- “Do the original performance scales have all required properties for a rightful application of the considered method?” This question addresses the problem discussed above; the problem of translating between scales of performance e.g. verbal and numerical. If the answer to the question is “no”, then the expert needs to check if it is possible, via coding or otherwise, to translate between the scales in a meaningful way. If so, then the MCDM technique can be considered for use.

- "Is it simple or hard (even impossible) to get preference information that the method requires?" Preference information is required by the expert to utilise the method, and is knowledge of how the decision-maker (the CA in this case) would make decisions about the use of the MCDM technique – primarily ranking and scoring of options. It assumes that the expert is meaningfully inserted into the decision-making process and can elaborate meaningful results from the decision-making process. If this is not possible with the MCDM technique being considered, then it should be discounted.
- "Should the part of imprecision, uncertainty or indetermination in the definition of performances be taken into account, and if so, in what way?" Generally, it is very rare to elicit information in an MCDM process without any uncertainty; performance criteria may have some ambiguity in their definition, as can the way in which criteria model performances. The way in which an MCDM technique handles such uncertainty can therefore be important.
- "Is the compensation of bad performances on some criteria by good ones on other criteria acceptable?" MCDM techniques which use additive methods offer this kind of compensation. Other MCDM techniques synthesise a criterion through aggregation of criteria; such techniques limit this kind of compensation. Others that rely on decision rules such as "if…then..." do not allow compensation at all.
- "Is it necessary to take into account some forms of interaction among criteria?" Most MCDM techniques do not allow for interaction between criteria; they should be chosen on the basis that they are independent. If this is not possible, an MCDM technique that can handle criteria interaction should be selected.

Stage 3; if the above questions fail to narrow the field down sufficiently, the following questions can be considered (again, in no particular order):

- "Is the method able to satisfy properly the needs of comprehension from the part of stakeholders involved in the decision process?" The decision-makers will need to be sufficiently satisfied that the MCDM process has been used to select the most appropriate option for their needs; comprehension of the MCDM technique will play a role in this.
- "Is an axiomatic characterization of the method available, and if so, is it acceptable in the considered decision context?" This essentially refers to

whether or not the decision-maker accepts the axioms of the stated MCDM technique, if they are available. If not, then the technique ought not to be used.

- "Can the weak points of the method affect the final choice?" All MCDM techniques have their weak points and these should be explored in making the final decision as to which technique to use in the specific decision-making context.

Considering these final points ought to reveal a suitable MCDM technique for use in the particular analysis at hand. The Roy and Słowiński technique is most effective when applied by an expert group; as discussed in introduction to Chapter 2, the author has 4 years of accumulated knowledge working with CES analysis tools and methods. Within the scope of this research, the author's experience was considered a suitable proxy for such an expert group. The following sections shall determine the most appropriate MCDM technique(s) to be used as the basis of decision-making frameworks to select demand and LZCT assessment methods and modelling tools for CES analysis.

4.3. MCDM technique selection process – stage 1

Stage 1 of the Roy and Słowiński process first asks:

"Taking into account the context of the decision process, what type(s) of results the method is expected to bring, so as to allow elaboration of relevant answers to questions asked by the decision maker?"

In the context of this research, the adopted MCDM technique(s) needs to select the most appropriate demand and LZCT assessment methods and modelling tools from those available. Ranking would select the best from those available; however this is only relative to the other options and does not give an indication of overall performance. Knowing the overall quality would be more useful, so that caution can be applied in the use of a method, or that mitigation measures to improve scores can be employed; therefore it would be more useful to score in a global sense rather than a relative sense. A subset of options is not required; ideally one, but possibly a combination of options can be selected. From this, a numerical value is required to be assigned to each option.

The following MCDM techniques provide this output:

- MAVT/MAUT techniques (already described above in Section 2.7).
- Analytical Hierarchy Process (AHP) [144]
- Simple Multi-Attribute Rating Technique (SMART) [145], SMART using Swings [SMARTS] and SMART Exploiting Ranks [SMARTER] [101]
- Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) [146]
- Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [147]
- Evaluation based on Distance from Average Solution (EDAS) [148]
- Choquet Integral [149]
- Commercial Off The Shelf Software Selection Process(COTSSSP) [105]

4.4. MCDM technique selection process – stage 2

Continuing the Roy and Słowiński process, two of the questions from stage 2 proved useful in narrowing down the choice of MCDM technique(s); the first was:

“Is the compensation of bad performances on some criteria by good ones on other criteria acceptable?”

Using an MCDM technique to select from a range of demand and LZCT assessment methods and modelling tools will involve the scoring of certain (yet to be defined) criteria. Compensatory MCDM techniques allow for compensation of bad performance on some criteria by good performance on others, meaning that this “bad” performance is not reflected in the overall score. However, some criteria may be extremely important such that a poor score (below certain thresholds) on these criteria is unacceptable and would mean that the method being scored would be discounted without some form of mitigation. All of the techniques listed above - with the exception of the COTSSSP software selection process - are compensatory MCDM techniques and thus would require some modification or combination with other techniques if taken forward to form the basis of any of the frameworks.

The second question which was useful was:

“Is it necessary to take into account some forms of interaction among criteria?”

Whilst we cannot know exactly if this is important before the criteria are defined, interaction between criteria is an extremely complex process and is difficult to model Therefore the vast majority of MCDM techniques require criteria to be selected on the basis that there is no interaction between them; this approach shall be taken in this research and thus the Choquet Integral technique – which specifically models interaction – shall be discounted from consideration. It will of course need to be ensured that there indeed is no interaction between criteria when they are selected; this will be tested "by asking, for each criterion, whether the preference scores of an option on one criterion can be assigned independently of knowledge of the preference scores on all the other criteria." [100].

4.5. MCDM technique selection process – stage 3

The following questions from Roy and Słowiński are then posed in stage 3:

"Is the method able to satisfy properly the needs of comprehension from the part of stakeholders involved in the decision process?",

"Is an axiomatic characterization of the method available, and if so, is it acceptable in the considered decision context?",

and

"Can the weak points of the method affect the final choice?"

The most pertinent question is the latter as it relates to the overall robustness of the technique, but the former two, which relate to the comprehension and acceptance of the method on the part of the decision-maker, shall also be considered in making a final choice. All MCDM techniques are known to suffer from weaknesses, which have been well-documented by others e.g. [103], [150], [151] The question is whether or not these particular weaknesses are relevant in the context of developing frameworks for demand and LZCT assessment methods and modelling tool selection. The MCDM techniques listed above shall therefore be briefly reviewed, and their strengths and weaknesses with regards to this research discussed; synergistic combinations of MCDM techniques will also be explored. This review will form a basis for an appropriate MCDM technique or combination of techniques shall be selected.

4.5.1. AHP

AHP [152] is a hierarchical model which breaks down a problem so that all of the available options are scored on how well they satisfy the overall aim, based on their performance with respect to criteria. It uses “pairwise comparison” to aid in ranking for both deriving criteria weights and how well options score on criteria [152]. This process requires the relative importance of all criteria to be judged, using a scale which converts verbal to numerical comparisons [144].

Matrices are then constructed which contain all comparative scores between criteria. Relatively complex arithmetic using the eigenvector method then defines weights for all criteria. This is usually performed by AHP software which search for the weights which best fits the comparisons made. Another, simpler way is the geometric mean method. This is performed by finding the geometric mean of each matrix row, and then normalised by dividing each row geometric mean by the total of all geometric means, to arrive at a weight for each criterion. The weights derived by this method are usually very close to those arrived at by the eigenvector method [102].

Once criteria weights are established, the next step involves the creation of matrices which record the relative importance scores for each of the options on each criterion. This means that if there are n criteria and m options, n matrices, $m \times m$ must be created. The relative performance scores are established using the same scale as before and either the eigenvector or geometric mean method used to calculate the performance score for each criterion on each option. Linear addition is then used to gain an overall score for each option.

AHP has been used for several uses in varied fields since its inception e.g. risk management in wind energy planning [153], resource allocation in agricultural projects [154], managing water quality in intensive fish farming [155], prioritising safety investments in the chemical industry [156] and assessing social vulnerability to earthquake disasters [157].

The main advantage of AHP is that it provides an intuitive framework for decision-makers, as pairwise comparisons are simple to perform; this is likely the main reason for its popularity but does assume that the decision maker is acting with full knowledge of the problem at hand [158] . There are also concerns about the validity of AHP. Firstly, it assumes correspondence between the scales; for instance, by saying that criterion A is clearly preferred over criterion B, this translates numerically to A being 5 times more important than B. This may not be true, however. Additionally, the scale can have problems with consistency e.g. if A is 3 times more important than B and B is 5 times more important than C, A should be 15 times more important than C – an impossibility using this scale [102], [150]. There can also be circular comparisons such as “Criterion A is more important than B, B is more important than C and C is more important than A” – another impossibility.

AHP is also known to suffer from the phenomenon of “rank reversal” i.e. the effect that by adding a criterion, two completely independent criteria then have their rankings reversed [103]. It has been suggested that this is due to the requirement for normalisation [159]. It has also been shown that many other methods including linear additive models can suffer from this phenomenon [160]. The debate over rank reversal remains unresolved, with several proposals – and corresponding rebuttals – for its resolution being published [160], [161]. It has been acknowledged that the rank reversal is unlikely to be a problem if the number of criteria is small; however as the number of criteria increases it may become increasingly difficult to control. To mitigate this, the number of criteria should be small – between 5 and 9 [152].

4.5.2. SMARTS and SMARTER

SMARTS and SMARTER are based on SMART; a linear additive model which was subsequently updated to correct a flaw in its logic [101]. They are a simple form of MAVT and require a limited number of criteria; usually 8 are sufficient as more would lead to a number of insignificant criteria with very low weights [102]. These are then weighted – in SMARTS this is done through “direct rating” by the decision maker to assign “true” weights. These are “swing” weights whereby the criteria are ranked, with the most important one being weighted 100. Other criteria are then weighted relative to this, and then all weights normalised so they sum to 100 [145]. In SMARTER they are ranked in order of importance with surrogate weights being assigned and then used to approximate “true” weights. The process is estimated to yield results 98% as accurate as direct rating [101]; it has been suggested that using weight approximations is more accurate than direct rating, as decision makers may be more confident and competent in simply ranking criteria [162] – this is extremely advantageous and increases consistency with decision-making.

For both SMARTS and SMARTER, each option is scored against each criterion, with all scores being multiplied by their respective weights and then summed to determine the most appropriate option [163]. SMARTS/SMARTER has the advantage that any weight assignment method can be used – generally there are two ways of scoring; either using global or local scaling. Global scaling has the advantage that any new option can be considered; local scaling may not allow for this. Additionally, due to considering only one part of the global scale, local scaling can give erroneously large scores and an overemphasis of small differences; global scaling does not suffer from this problem [164]. Whilst it can be a challenge to define what exactly the worst and best possible performances are when using global scaling, it considers the options in the wider context rather than only looking for the best performing option of those under consideration, and thus allows new options to be considered.

SMART, SMARTS and SMARTER have been widely used, with SMART being used to aid decisions in e.g., optimising deployment of battlefield renewable energy generation systems [165] and selecting the best location for a business, SMARTS being used for e.g., quantitative evaluation of project delivery systems [166] and SMARTER being used e.g., to select and evaluate suppliers in the construction industry [167] and assess the suitability of electricity generation sectors in South Asia [168].

Both SMARTS and SMARTER are advantageous in that their structure is very similar to cost benefit analysis; this will feel familiar to many users and be easily understood [102]. The techniques are also intuitive and clear to use. However, SMARTS or SMARTER are not recommended for use as an initial screening process as they tend to over-simplify the problem, leaving very similar alternatives to be considered [169] . This can be prevented by performing a screening process with different weights, with options performing consistently well being taken forward for further analysis [102]. Alternatively a complementary MCDM technique could be employed for this purpose.

4.5.3. MACBETH

MACBETH is a linear additive MDCM technique formulated around a decision tree. Decision makers must first define the criteria which form the decision tree. The performance of the options on these criteria is then judged using an ordinal scale. Next, pairwise comparisons matrices are used to make a qualitative judgement on the attractiveness of options; these comparisons use a scale from 0-6, with 0 being "indifference between the alternatives" and 6 being "an alternative is extremely attractive over another". Criteria are also judged in a similar way. Linear programming is then used to transform these judgements onto a MACBETH scale.

MACBETH has been used successfully in applications such as evaluating hydrogen storage technologies [170], assessing and ranking street redesign potential [171], resource allocation to roads construction [172], evaluation of bids in public calls for tender [173] and prioritising maintenance, repair and refurbishment of housing [174].

MACBETH provides a clear, intuitive framework for decision makers to use, and has a clear advantage over the similar AHP technique in that the consistency of pairwise comparisons judgements can be checked using the linear programming; the linear program will be infeasible with inconsistencies. The problem of rank reversal with pairwise comparisons (discussed above), however, is still present.

4.5.4. TOPSIS

TOPSIS [147] is based upon the premise of finding the best solution by simultaneously minimising the Euclidian distance from the Positive Ideal Solution (PIS) and minimising the distance from the Negative Ideal Solution (NIS). The PIS seeks to maximisation of the benefit criteria and minimisation of cost criteria; NIS seeks the opposite. First, a matrix of options and criteria is constructed; this is then normalised. The weighted decision matric is then calculated by using criteria weights to multiply the columns on the normalised matrix. The PIS and the NIS are determined, and the separation measures between options, the PIS and NIS are calculated. The relative closeness to the PIS is calculated for each option; the closer this is, the more "ideal" the option, allowing all options to be scored and ranked.

TOPSIS has been used widely in multi criteria decision making applications e.g. performance evaluation for airlines [175], financial performance of technology firms [176], human resources selection [177] and supplier selection in the manufacturing industry [178].

Due to the lack of pairwise comparisons, TOPSIS may be well-suited to problems with a large number of criteria and options. This is especially true of qualitative judgements [179].

However, as the number of options increase, so does the likelihood of rank reversal – especially if there are over 50 [180]. However, TOPSIS has no way for eliciting weights, other than through “direct rating” by the decision maker. This is a major weakness with respect to the assessment of assessment methods and modelling tools, as the decision maker may find it very difficult to elicit weights. Additionally there is no process for checking consistency of judgements [181].

4.5.5. EDAS

EDAS [148] is based upon a similar premise to TOPSIS; however in EDAS, the best solution is determined by the distance from the average solution (AV). The solution is a function of the positive and negative distance from the AV (PDA and NDA, respectively). Criteria and options are determined, and then a matrix is constructed to capture the performance of all options on the criteria. AV is then determined using a function, and then PDA and NDA matrices are constructed based on criteria type – benefit or negative, and an appraisal score for each option is calculated using another function. From the appraisal score, options are then ranked.

EDAS is a relatively new technique and thus there are few examples available of its use. It has been used for the evaluation of quality in contractor contracts [182], assessing the performance of public banks [183] and evaluating smartphones in the Indian market [184]. The primary strength of EDAS is that unlike TOPSIS, there is no need for the user to determine the ideal and nadir solutions. However, there is no process for eliciting weights. In cases where this information is difficult to elicit from a decision-maker, there may be a need to synthesise these weights through another technique. Additionally, due to the lack of pairwise comparisons, it may be well-suited to problems with a large number of criteria and options. This is especially true of qualitative judgements [179]. EDAS performs better than TOPSIS in terms of rank reversal; it is however very likely to occur as the number of options increases – especially if there are over 50 [180].

4.5.6. COTSSSP

COTSSSP [105] was developed by Sandia National Laboratories to aid in the selection of software in an effort to save time, money and effort. The process aim was to "systematically evaluate, rank and select software that best meets the project requirements."

The COTSSSP works on the basis of project requirements – these are the criteria against each option (software package) is scored. It is not, however, a linear additive model as the criteria have no weights. They are simply assigned "essential", "desirable" or "not applicable". A level one filter is first applied to all options; only those which meet all "essential" criteria pass this filter. The options which pass this filter are then judged according to their "desirable" features; the level two filter. The way in which they are judged according to their "desirable" features involves defining measurable criteria by which they can be judged and creating case studies to use the software packages and analyse their performance.

The COTSSSP has a clear advantage in that it does not – in the stage one filter – allow for compensation of bad performances on some criteria by good ones on other criteria. This could be used advantageously in the selection of demand and LZCT assessment methods and modelling tools. The level two filter, when the COTSSSP was put into practice [185], was applied using pair-wise comparison and a Pugh matrix to compare the software tools. As discussed above, pair-wise comparison can have the problem of rank reversal. The Pugh matrix and pair-wise comparison are not integral components of COTSSSP, however – they were simply used as a means of ranking the sub-set of options provided. Any other MCDM technique e.g. a linear additive technique could be used to perform the same function. The logic and application of COTSSSP is also straightforward and clear, and will be able to be understood by most decision makers.

4.6. Selection of MCDM technique(s) to develop a framework for selection of Demand Assessment Methods for a Community Energy System

The previous sections (4.2-4.4) follow the MCDM technique selection process of Roy and Słowiński [107] looking at methods appropriate to the CES domain for selecting demand and LZCT assessment methods and also modelling tool selection in general. In this section we consider the specific case of selecting MCDM techniques to form the basis of a demand assessment method selection framework.

Continuing stage 3 of the Roy and Słowiński MCDM technique selection process [107] – and looking specifically at the selection of demand assessment methods - we are to consider the following questions:

“Is the method able to satisfy properly the needs of comprehension from the part of stakeholders involved in the decision process?”,

“Is an axiomatic characterization of the method available, and if so, is it acceptable in the considered decision context?”,

and “Can the weak points of the method affect the final choice?”

In selecting demand assessment methods, it is likely that the criteria used will be a combination of both binary choices in scoring – i.e. inclusion or not of a certain feature – and judgements on a scale about e.g. the quality of the method, the robustness of the underlying calculations, the reliability of the data etc. Therefore the scoring system used in the selected MCDM technique(s) will need to consider this. No one technique is capable of this.

As discussed above, COTSSSP is especially advantageous when compared to the other MCDM techniques as it is a non-compensatory technique which has the ability to filter options based on their inclusion/omission of capabilities. COTSSSPs main contribution to MCDM is the classification of criteria into “essential”, “desirable” and “not relevant”. COTSSSP however can result in a number of different options with a similar profile for essential and desirable features and does not differentiate so does not directly support a clear decision. For example, once COTSSSPs was performed in [185], a pair-wise comparison method had then to be used to allow a selection decision to be made.

An alternate MCDM technique other than the pair-wise comparison method could then usefully be used in conjunction with the COTSSSP to select demand assessment methods for a CES; an MCDM technique which includes a way of eliciting weights and subsequent scoring would be very useful.

AHP and SMARTER are the strongest candidates for this secondary role. Although they are both compensatory techniques, meaning that they compensate for poor performance on one criterion with strong performance on another, in this secondary role this would potentially not be as much of a concern. Of the two methods, it appears there is more criticism of AHP, regarding problems with rank reversal and the fact that criteria are not weighted relative to their scale. SMARTER is therefore advantageous over AHP when asking the question: “Can the weak points of the method affect the final choice?”.

SMARTER is simple to use and intuitive, with easy-to-understand results. It therefore satisfies the questions “Is the method able to satisfy properly the needs of comprehension from the part of stakeholders involved in the decision process?”, and Is an axiomatic characterization of the method available, and if so, is it acceptable in the considered decision context?”,

There is good precedent of MCDM techniques being combined to create a hybrid technique, suitable for the particular case study and using techniques which mitigate for each other’s shortcomings [139]–[143]. Such an approach could be usefully employed here. The combination of COTSSSP and SMARTER will allow for the strengths of either technique to compensate for the weaknesses of the other, to create a more robust overall technique for the requirements of the decision-making framework. In addition, the frameworks follow logic and incorporate axioms which will be easily understood and accepted by the majority of decision makers.

Taking this into account, the combination of COTSSSP and SMARTER is therefore an ideal choice. This combination shall therefore be taken forwards for use as the basis of a framework for demand assessment method selection. COTSSSP will allow the hybrid technique to ensure that only methods with all “essential” criteria are considered without mitigation, so that the problems associated with compensatory MCDM techniques (of which SMARTER is one) are mitigated for. It will allow a filtering of methods to take place, and of areas of poor performance to be identified.

The use of SMARTER will allow options which pass the filter to be weighted and scored in a clear and intuitive manner such that the most appropriate option(s) can be identified.

For ease of use, the SMARTER tables shall be used, with all criteria being judged if they are “essential” or “desirable” or “not relevant”. All criteria will be weighted according to the SMARTER technique of using surrogate weights; those judged to be “essential” will either receive the maximum score possible of 100 if the method includes the criterion, or zero if the method does not include the criterion. Any method scoring zero on any criterion will not be able to be considered for use without mitigation. The criteria judged to be “desirable” will then be used to judge options on their performance on these criteria on a scale of 0-100. The highest scoring method will then be the most appropriate for use in the case study. In addition, it is recommended that methods with a low score for any “desirable” criterion are applied with caution. Scoring in this way will also allow the identification of synergistic combinations of methods. E.g., if a method scores well on several points but scores zero or low on any criterion, this will be easily visible and there may be scope to combine this method with another so that this zero score is mitigated for through combination with another method. This is, in reality, how experts conduct analyses of CESs but the process is neither formalised nor documented. This framework aims to address this gap.

The use of COTSSSP and SMARTER to form an intuitive, simple to use framework for the selection of demand assessment methods for a CES is outlined in Chapter 5, and an example of it in use for a case study is outlined in Chapter 6.

4.7. Selection of MCDM technique(s) to develop a framework for selection of LZCT Assessment Methods for a Community Energy System

Sections 4.2-4.4 follow the MCDM technique selection process of Roy and Słowiński [107] looking at methods appropriate to the CES domain for selecting demand and LZCT assessment methods and also modelling tool selection in general. In this section we consider the specific case of selecting MCDM techniques to form the basis of an LZCT assessment method selection framework.

Continuing stage 3 of the Roy and Słowiński MCDM technique selection process [107] – and looking specifically at the selection of demand assessment methods - we are to consider the following questions:

“Is the method able to satisfy properly the needs of comprehension from the part of stakeholders involved in the decision process?”,

“Is an axiomatic characterization of the method available, and if so, is it acceptable in the considered decision context?”,

and “Can the weak points of the method affect the final choice?”

In selecting LZCT assessment methods, it is likely that the criteria used will be a combination of both binary choices in scoring – i.e. inclusion or not of a certain feature – and judgements on a scale about e.g. the quality of the method, the robustness of the underlying calculations, the reliability of the data etc. Therefore the scoring system used in the selected MCDM technique(s) will need to consider this. No one technique is capable of this.

As discussed above, COTSSSP is especially advantageous when compared to the other MCDM techniques as it is a non-compensatory technique which has the ability to filter options based on their inclusion/omission of capabilities. COTSSSPs main contribution to MCDM is the classification of criteria into "essential", "desirable" and "not relevant". COTSSSP however can result in a number of different options with a similar profile for essential and desirable features and does not differentiate so does not directly support a clear decision. For example, once COTSSSPs was performed in [185], a pair-wise comparison method had then to be used to allow a selection decision to be made.

An alternate MCDM technique other than the pair-wise comparison method could then usefully be used in conjunction with the COTSSSP to select demand assessment methods for a CES; an MCDM technique which includes a way of eliciting weights and subsequent scoring would be very useful.

AHP and SMARTER are the strongest candidates for this secondary role. Although they are both compensatory techniques, meaning that they compensate for poor performance on one criterion with strong performance on another, in this secondary role this would potentially not be as much of a concern. Of the two methods, it appears there is more criticism of AHP, regarding problems with rank reversal and the fact that criteria are not weighted relative to their scale. SMARTER is therefore advantageous over AHP when asking the question: "Can the weak points of the method affect the final choice?".

SMARTER is simple to use and intuitive, with easy-to-understand results. It therefore satisfies the questions "Is the method able to satisfy properly the needs of comprehension from the part of stakeholders involved in the decision process?", and Is an axiomatic characterization of the method available, and if so, is it acceptable in the considered decision context?", There is good precedent of MCDM techniques being combined to create a hybrid technique, suitable for the particular case study and using techniques which mitigate for each other's shortcomings [139]–[143]. Such an approach could be usefully employed here. The combination of COTSSSP and SMARTER will allow for the strengths of either technique to compensate for the weaknesses of the other, to create a more robust overall technique for the requirements of the decision-making framework. In addition, the frameworks follow logic and incorporate axioms which will be easily understood and accepted by the majority of decision makers.

Taking this into account, the combination of COTSSSP and SMARTER is therefore an ideal choice. This combination shall therefore be taken forwards for use as the basis of a framework for LZCT assessment method selection. COTSSSP will allow the hybrid technique to ensure that only methods with all "essential" criteria are considered without mitigation, so that the problems associated with compensatory MCDM techniques (of which SMARTER is one) are mitigated for. It will allow a filtering of methods to take place, and of areas of poor performance to be identified.

The use of COTSSSP and SMARTER to form an intuitive, simple to use framework for the selection of LZCT assessment methods for a CES is outlined in Chapter 5, and an example of it in use for a case study is outlined in Chapter 6.

4.8. Selection of MCDM technique(s) to develop a framework for selection of Modelling Tools for a Community Energy System

Sections 4.2-4.4 follow the MCDM technique selection process of Roy and Słowiński [107] looking at methods appropriate to the CES domain for selecting demand and LZCT assessment methods and also modelling tool selection in general. In this section we consider the specific case of selecting MCDM techniques to form the basis of a CES modelling tool selection framework.

Continuing with stage 3 of the Roy and Słowiński MCDM technique selection process [107] – and looking specifically at the selection of modelling tools - we are to consider the following questions:

“Is the method able to satisfy properly the needs of comprehension from the part of stakeholders involved in the decision process?”,

“Is an axiomatic characterization of the method available, and if so, is it acceptable in the considered decision context?”,

and “Can the weak points of the method affect the final choice?”

The MCDM techniques selected to form the basis of demand and LZCT assessment method selection frameworks (COTSSSP and SMARTER) were selected in combination due to the capability of COTSSSP to filter and eliminate from consideration demand and LZCT methods which do not meet certain criteria. Then SMARTER can score and rank methods based on their performance on the remaining criteria.

Modelling tools have many different capabilities, which will be used to determine the MCDM selection criteria. This number of criteria is likely to exceed the number of criteria recommended for the application of SMARTER (8), which will be ineffective for use due to many criteria with similar weights. In addition, a deep knowledge is required to score against criteria in SMARTER; to develop knowledge of several tools in order to score them effectively is likely to be an extremely long and arduous process. In addition. COTSSSP was developed specifically for the selection of software tools and has been used successfully in this application [105]. It is therefore also suited to the selection of modelling tools (which can also classed as software tools). Therefore, the use of the COTSSSP technique alone will be used as the basis for selection of modelling tools.

Modelling tool capabilities will be categorised, documented, and judged “essential”, “desirable” or “not relevant” to a particular case study using COTSSSP. Tools which do not incorporate “essential” capabilities can be discounted, and a subset of tools which include more of the “desirable” capabilities can be generated. This will allow for the further investigation of these tools by the expert for CES analysis. This can also include the use of COTSSSP in two stages, with the first stage being higher level in order to perform an initial filter on tools.

The use of COTSSSP to form a framework for the selection of CES modelling tools for a CES is outlined in Chapter 8, and an example of it in use for a case study is outlined in Chapter 9.

4.9. Chapter 4 conclusion

This chapter aimed to select MCDM techniques to form the basis of the decision-making frameworks for selection of (i) demand assessment methods, (ii) LZCT assessment methods and (iii) modelling tools for CES analysis. This has been achieved by using the literature review in Chapter 2 to provide information on processes to select the most appropriate MCDM technique for a given purpose. This led to the selection of the Roy and Słowiński MCDM technique selection process, which asks a series of questions in successive stages to narrow down the choice of MCDM techniques [107]. These questions asked what kind of results were required from the MDCM technique, if compensatory techniques were acceptable, the strengths and weaknesses of the candidate techniques and if results would be easily understood by the community agent.

To effectively select demand and LZCT assessment methods, it was decided that a hybrid MCDM technique of COTSSSP and SMARTER be used. This has the advantage in that COTSSSP can be used as a filter by deeming criteria “essential”, “desirable” and “not relevant”. Methods incorporating all “essential” criteria will score 100 for those criteria, and zero for the non-inclusion of any “essential” criteria. Methods scoring zero on any criteria will not be considered for use without mitigation. Criteria are then weighted according to SMARTER, which uses surrogate weights to make the process more consistent and simple. Options are then scored based on their performance on criteria. In this way, simple, intuitive frameworks can be developed, which identifies opportunities for methods to be synergistically combined.

For the modelling tool selection framework, COTSSSP was selected. This is because tools are complex and to develop criteria based on all capabilities would be beyond the capabilities of the MCDM technique, as well as being overly arduous for the decision maker to learn all tool capabilities sufficiently. COTSSSP instead allows the decision-maker to filter the tools based on their inclusion of “essential” criteria. They can then be judged as to the number of “desirable” criteria they include, with similarly scoring tools being taken forward for further scrutiny.

The inclusion of two types of framework has the advantage in that it will allow for the comparison of both.

5. Chapter 5 - MCDM Frameworks for Selection of Demand and LZCT Assessment Methods. Use of COTSSSP and SMARTER to Develop Frameworks to Select Demand and LZCT Assessment Methods for Community Energy Systems

5.1. Chapter 5 introduction.

It has been established in Chapter 4 that a combination of the COTSSSP [105] and SMARTER [101] MCDM techniques shall be taken forwards as the basis of MCDM frameworks to select demand and LZCT assessment methods for CES analysis. This chapter will develop the frameworks by (i) defining criteria used to judge methods, (ii) defining a scoring system, and (iii) defining scoring guidelines. The frameworks will then be demonstrated through application to a case study in Chapters 6 and 7 for the demand assessment method and LZCT assessment method selection frameworks, respectively.

The scope of work here is limited to demand and LZCT assessment methods suitable for assessing demand and LZCTs at a community-scale. It was found through development of these frameworks that the same criteria apply for judging both demand and LZCT assessment methods; therefore they are both covered in this chapter.

5.2. Definition of criteria, scoring system and scoring guidelines to judge Demand and LZCT Assessment Methods

The use of COTSSSP and SMARTER to select the most appropriate demand and LZCT assessment methods first involves the definition of criteria and scoring guidelines. MCDM application should be guided by input from an expert team. As discussed in introduction to Chapter 2, the author has 4 years of accumulated knowledge working with CES analysis tools and methods. Within the scope of this research, the author’s experience was considered a suitable proxy for an expert team. In addition, the author worked as part of a decision-making team made up of energy experts from a university department with experience in CES development, with input from industry energy consultants.

Best practice in setting criteria is to first consider the objectives to be achieved by the MCDM process [100]. The objective here is to select the most appropriate assessment method or combination of methods for each energy demand and LZCT, so they can be applied to generate inputs for CES modelling.

COTSSSP can handle a large number of criteria; SMARTER limits the number of criteria to 8 [102], as to have more than this means there will be unnecessary work in defining and scoring criteria which have insignificantly small weights and negligible impact on the overall score. The criteria are checked for completeness, redundancy, functionality, preferential independence, double-counting, number and time-dependent impacts [102].

Once criteria are chosen, the next challenge is to define scoring to represent performance. Of particular interest may be score thresholds which if not met can indicate an option is “not viable” due to a low overall score or score on individual criteria. Likewise it may not include “essential” capabilities. Such methods will be unsuitable for use unless mitigation is applied. Pair-wise comparisons can be used to check consistency of judgements [186]; this is when options are compared with every other option on the performance of individual criteria to ascertain if one is better than the other.

Brainstorming was carried out and expert meetings were held to define criteria according the above requirements; from this, three main themes or groupings of criteria became apparent.

The first theme, “**method quality**”, reflects that the methods and embedded calculations and assumptions should be well validated and that the method produces useful output. Two criteria are associated with this theme; “**method validity**” and “**output suitability**”.

The second theme “**input data**” reflects the provenance of the input data and level of confidence associated with the data accuracy. The criteria associated with this theme are “**input data resolution**” and “**input data integrity**”.

The third theme is “**practical considerations**” which reflects practicalities of method implementation; criteria falling under this theme are “**process clarity**” and “**resource requirement**”.

It may be the case that LZCTs do not have immediately accessible assessment methods, if this is the case then it is important that these technologies are not excluded from consideration, rather it is recommended that more extensive expert input is sought.

The following sections expand on the themes, criteria, scoring systems, scoring guidelines and processes.

5.2.1. Method quality theme – criteria, scoring system and scoring guidelines

Whilst some methods may have a plethora of available literature available, simply because many bodies, academics etc. have chosen to use it, this is not necessarily an indication of a high quality level. Additionally, there may be little or no literature available for newer methods, due to insufficient available time for a body of literature to accumulate. Therefore, scrutiny of the method via interrogation of method robustness and requirements is more effective way to judge method quality.

High quality methods will likely include documentation; this should show the methodology in a high level of detail documenting and justifying robust underlying calculations. Such methods are more likely to be able to be relied upon with a high level of confidence. Supplementary to method documentation, case studies may exist showing the method in use, illustrating or validating its underlying quality.

Demand and LZCT assessment methods should output data compatible with modelling of a CES. Hourly or sub-hourly timesteps are generally accepted as required to model energy systems due to the stochastic nature of renewables and peak demands [39]. At smaller scales (e.g. in CESs) there is little "smoothing" effect of demand or supply profiles experienced at a regional or national scale; demand diversity is therefore important.

Considering the above, methods will be judged according to two criteria:

- "Method validity". This describes the level of detail of underlying calculations within the method, and how robust they are. This is deemed a "desirable" criterion and will be scored on a scale of 0-100.
- "Output suitability" relates to the resolution (hourly, monthly, annual etc.) of the data output by the method i.e. a demand or LZCT energy profile, which should be hourly or sub-hourly. This is an "essential" criterion, and will be scored 100 for methods providing hourly or sub-hourly output; otherwise the method will score 0 for this criterion and the method will be deemed unsuitable for use (without some form of mitigation e.g. combination with a further method).

Direct Rating, to score the criteria employing scores of 0 (non-scoring), 25 (low score), 50 (intermediate score), 75 (high intermediate score) and 100 (high score) shall be used to consider these points, as there is no pre-existing scale on which they can be judged. These scores were selected as they are intuitive to most decision makers who will be familiar with a scale on which 0 = no score and 100 = the best possible score; a scale of 0-100 is also the scale employed by SMARTER. In earlier iterations of the framework the full range of scores from 0-100 was incorporated; this was too ambiguous, however, and it was not possible to define scoring guidelines which would ensure consistency in the use of the framework. Therefore, clear guidelines for scores 0, 25, 50, 75 and 100 were defined to ensure this consistency.

It was further asserted that methods scoring zero for "Method validity" should not be used unless some mitigation steps were taken; this approach was extended to all criteria i.e. a method scoring zero in any criteria should not be used without mitigation. The fact that COTSSSP has been used to class "Output suitability" as "essential" means that this will automatically occur for this criterion if the method produces anything at a lower resolution than hourly, so methods generating e.g. monthly or annual outputs will be excluded.

To ensure scoring is as consistent as possible, the guidelines laid out in Table 1 were developed.

Table 1 - Demand and LZCT assessment method criteria - Method quality

Method Quality					
Criterion	**Score = 0**	**Score= 25**	**Score = 50**	**Score = 75**	**Score = 100**
Method validity	No underlying documentation or calculations of available. No literature documenting method. Method cannot be verified.	Extremely shallow detail. Supporting documentation (if available), publications etc. show underlying	Intermediate score	Supporting documentation and case studies show underlying calculation methods to be of a reasonably high quality, but with some flaws.	Supporting documentation shows underlying calculation methods to be robust. Method is, e.g., produced by reputable body,

	Method is produced by a little-known or unreputable body. Method cannot be used without mitigation.	calculation methods to be weak. Apply caution in the use of this method; consider mitigation through use of complementary methods		Method may have been produced my reputable body using well-established calculations, but may have been shown to have some issues.	based on national standards, or is industry-standard. Method has been verified by reputable body or in publications. Case studies are available showing the method to be robust.
Output suitability	No output data or the method produces data at anything more than an hourly time-step. Method cannot be used without mitigation	n/a	n/a		Data is produced at an hourly or sub-hourly time-step

5.2.2. *Input data theme – criteria, scoring system and scoring guidelines*

Method output quality relies heavily on input data, often from multiple sources, which ideally covers several years to capture variations with weather and behavioural changes etc.

Where methods require temporal inputs, direct inputs with hourly or sub-hourly timesteps are optimal rather than monthly or annual inputs.

Reliable and useful temporal data will also have been collected over several years and an average annual profile be obtainable.

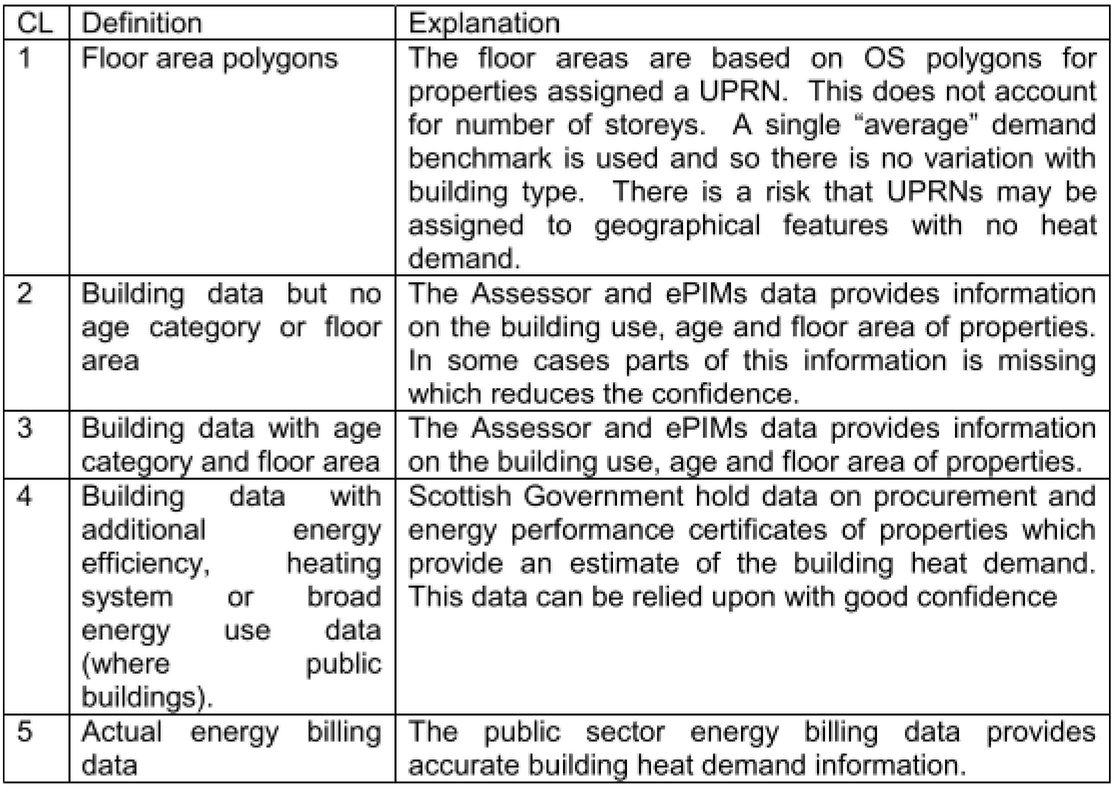
There may be factors which can cause uncertainty and possible error in input data leading to questionable input data integrity; this would need to be checked via monitoring and evaluation of data.

Due to interruptions in measurements etc. there may be data gaps; leading to synthesised data being used to fill in. Data also may have been collected over a short time period and synthesised and extrapolated to cover an entire year etc.

Some methods require physical input parameters from which they will calculate the outputs e.g. building dimensions etc.; in such cases, higher resolution data is more desirable e.g. on-site direct survey data is preferred to assumed national averages etc.

The different datasets used to calculate heat demand for the Scottish Heat Map (shown in Table 2) is a useful reference for various levels of input data resolution.

Table 2 - Confidence levels (CL) and descriptions applied to heat demand data (from [44])



CL	Definition	Explanation
1	Floor area polygons	The floor areas are based on OS polygons for properties assigned a UPRN. This does not account for number of storeys. A single “average” demand benchmark is used and so there is no variation with building type. There is a risk that UPRNs may be assigned to geographical features with no heat demand.
2	Building data but no age category or floor area	The Assessor and ePIMs data provides information on the building use, age and floor area of properties. In some cases parts of this information is missing which reduces the confidence.
3	Building data with age category and floor area	The Assessor and ePIMs data provides information on the building use, age and floor area of properties.
4	Building data with additional energy efficiency, heating system or broad energy use data (where public buildings).	Scottish Government hold data on procurement and energy performance certificates of properties which provide an estimate of the building heat demand. This data can be relied upon with good confidence
5	Actual energy billing data	The public sector energy billing data provides accurate building heat demand information.

Data measured on-site (if collected properly) will be more reliable as there are often local peculiarities which cannot be accounted for remotely.

The data source is another indicator of input data integrity; data from a well-known and reputable body can be considered higher integrity than from an un-attributable source; data from a global database will have increased integrity if it is checked against independent local data references etc.

The above points are applicable to both demand and LZCT assessment methods; taking them into consideration, methods can be judged according to two criteria:

- “Input data resolution”. This describes the resolution - spatial, temporal or other qualitative measure - of data the method requires as inputs. This applies to both user-input data such as, e.g., survey data, and source data embedded within the method, e.g., weather datasets. This is deemed a “desirable” criterion and will be scored on a scale of 0-100.

- "Input data integrity" relates to the integrity of the input data required by the method. It covers three aspects: 1. data measurement period; 2. data accuracy (in relation to the site under consideration); 3. data reliability (i.e. if it has been independently verified or comes from a reliable source). This is deemed a "desirable" criterion and will be scored on a scale of 0-100.

These three "Input data integrity" sub-criteria will be ranked, weighted and scored separately for each method to form an overall weighted score for the "Input data integrity" criterion.

Some methods require a range of different data sources to be used – for example, PHPP requires building survey data in combination with climate data to determine heat demand for a building. So that the decision-making process is clear and consistent, it is important that the data sources are scored individually on their performance against each of the "Input data integrity" sub-criteria as well as the "Input data resolution" criterion. To perform this scoring, Input data sources ("Survey data" and "Climate data" in this example) will need to be ranked, weighted, and then scored on their performance against the "Input data integrity" sub-criteria ("Data measurement period", "Data accuracy" and "Data reliability") and the "Input data resolution" criterion, using the guidelines laid out in Table 3. This will allow overall weighted scores for each of the "Input data integrity" sub-criteria and the "Input data resolution" criterion to be produced, based on *all* data inputs. The process will be covered in more detail through application of the frameworks to a case study in Chapters 6 and 7 for demand and LZCT assessment method selection, respectively.

Direct Rating, to score the criteria employing scores of 0 (non-scoring), 25 (low score), 50 (intermediate score), 75 (high intermediate score) and 100 (high score) shall be used to consider these points, as there is no pre-existing scale on which they can be judged. These scores were selected as they are intuitive to most decision makers who will be familiar with a scale on which 0 = no score and 100 = the best possible score; a scale of 0-100 is also the scale employed by SMARTER. In earlier iterations of the framework the full range of scores from 0-100 was incorporated; this was too ambiguous, however, and it was not possible to define scoring guidelines which would ensure consistency in the use of the framework. Therefore, clear guidelines for scores 0, 25, 50, 75 and 100 were defined to ensure this consistency.

A score of 0 in any criteria indicates the method is unsuitable unless mitigation is carried out. To ensure consistency in scoring, the guidelines laid out in Table 3 were developed.

Table 3 - Demand and LZCT assessment method criteria – Input data

Input Data					
Criterion	**Score = 0**	**Score = 25**	**Score = 50**	**Score = 75**	**Score = 100**
Input data resolution	Data is unavailable Method cannot be used without mitigation	Data is at such a low resolution as to be only useful as a rough guide, if temporal e.g. annual. If physical measurements a lower level of detail is required – to the nearest 50m and with very rough estimates on material properties,	Intermediate score	Data is available at a daily resolution, if temporal. If physical measurements/qualities for building fabric measurements, a reasonably high level of resolution is required – to the nearest m and with estimates on material properties based on measured observations	Data is available at an hourly or sub-hourly resolution, if temporal. If physical measurements/qualities for building fabric measurements, a high level of resolution is required – to the mm and including material thicknesses and properties.

		if any.			
Input data Integrity	Data is unavailable Method cannot be used without mitigation.	Sub-criterion 1: data measurement period (if relevant) - data is very patchy, or measured over only a few days or less. Sub-criterion 2: data accuracy -	Intermediate score	Sub-criterion 1: Data measurement period - there is one year of data Sub-criterion 2: Data accuracy – data measured from comparable sites/buildings is available Sub-criterion 3: Data reliability – data source is a well-known and reliable body, has	Sub-criterion 1: Data measurement period - there are several years' worth of data Sub-criterion 2: Data accuracy – data measured on-site is available, or is able to be gathered. Sub-criterion 3: Data reliability – data source is a well-known and

		data is estimated from generic profiles, population, building footprint etc. Sub-criterion 3: data reliability – data source is unknown and unverified, or known to be unreliable Apply caution in the use of this method; consider mitigation through use of complementary		been independently verified to be reliable for the location, or has been measured on-site by an expert. There will, however, be some flaws with the data.	reliable body, has been independently verified to be reliable for the location, or has been measured on-site by an expert

		methods			

5.2.3. *Practical considerations theme – criteria and scoring guidelines*

This category looks at the practical aspects of selecting a method. The method needs to be used – but is it user friendly? Is there an intuitive way to use the method or not? There may also be a demand on resources to implement the method; it may require a lot of time, money, and a team to implement and there may be a requirement for expert interpretation of the method. These may all be readily available and therefore the requirement not a problem; conversely they may be unavailable or hard to source and therefore there requirement poses a barrier.

Considering this, methods will be judged according to two sub-criteria:

- “Process clarity” captures the implementation of the method. It is scored based on ease of use of the method; this is a function of method intuitiveness, available support and documentation. This is deemed a “desirable” criterion.
- “Resource requirement” is the demand on resources which the method places. These may be time, money, expertise etc.; different communities or agencies will be differently placed to meet them. This is deemed a “desirable” criterion.

Direct Rating, to score the criteria employing scores of 0 (non-scoring), 25 (low score), 50 (intermediate score), 75 (high intermediate score) and 100 (high score) shall be used to consider these points, as there is no pre-existing scale on which they can be judged. These scores were selected as they are intuitive to most decision makers who will be familiar with a scale on which 0 = no score and 100 = the best possible score; a scale of 0-100 is also the scale employed by SMARTER. In earlier iterations of the framework the full range of scores from 0-100 was incorporated; this was too ambiguous, however, and it was not possible to define scoring guidelines which would ensure consistency in the use of the framework. Therefore, clear guidelines for scores 0, 25, 50, 75 and 100 were defined to ensure this consistency.

Methods scoring zero in any criteria will be unable to be used without mitigation. To aid in this the scoring and to ensure consistency, the guidelines laid out in Table 4 were developed.

Table 4 - Demand and LZCT assessment method criteria – practical considerations

Practical considerations					
Criterion	**Score = 0**	**Score = 25**	**Score = 50**	**Score = 75**	**Score = 100**
Process clarity	There is no process to follow Method cannot be used without mitigation.	It is very unclear as to how the method is to be used. Apply caution in the use of this method; consider mitigation through use of complementary methods	Intermediate score.	There is a process to follow in implementing the method, but there are some flaws which mean the process is not entirely transparent or clear.	Use of the method is clear and intuitive e.g., there is a clear process to follow. That or the method has abundant support and documentation to assist in method implementation.

Resource requirement	The method is prohibitively demanding on resources. Method cannot be used without mitigation.	The method is extremely demanding on available resources which are very limited. Apply caution in the use of this method; consider mitigation through use of complementary methods	Intermediate score.	Resources to implement the method are available, but will take time/effort to procure.	Resources are readily available to implement the method.

5.2.4. Mitigation for methods with a zero score in "essential" or "desirable" criteria or with a low overall score

Methods scoring zero in any criteria are deemed unsuitable for use in isolation. Additionally, methods may receive a low score on criteria; the use of such methods in isolation must be conducted with caution. In all of the above cases, it is recommended that mitigation through a synthesis of methods through combination is sought. Once all methods acre scored, interrogation of the tables will reveal possible complementary combinations of methods; however only through expert analysis of methods is it possible to determine compatibility between methods and if indeed a synthesis is possible. Every beneficial combination should be explored and scored if possible. Indeed, possible combinations of methods which score highly on all criteria and with a high overall score should even be explored.

5.3. COTSSSP and SMARTER MCDM Demand and LZCT Assessment Method selection frameworks

The following outlines the MCDM demand and LZCT assessment method selection frameworks, which were developed to aid in the selection of appropriate methods for the analysis of a CES, based on the COTSSSP [105] and SMARTER [101] techniques.

Tables 5-11 lay out both frameworks for scoring demand and LZCT assessment methods.

Tables 5 and 6 contain the Input data sources for demand and LZCT assessment methods, respectively; these are only required for methods with multiple data sources. Tables 7 and 8 contain the sub-criteria for the “Input data integrity” criterion for demand and LZCT assessment methods, respectively. Tables 9 and 10 contain the overall scoring frameworks for demand and LZCT assessment methods, respectively. Table 11 contains the ROD weights to be used in criteria and sub-criteria weighting.

5.3.1. Step 1 - Identification of decision-makers and requirements of decision-making process

The first step of using the frameworks is to identify the decision-makers, requirements of the decision-making process, motivations and priorities of the community agent need to be established. Thorough knowledge of the community requirements and any sources of existing data also need to be identified. With this information, the criteria can be effectively ranked and scored according to the requirements of the case study.

5.3.2. Step 2 - Population of tables with methods

Tables 7, 8, 9 and 10 should be populated with a comprehensive list of demand and LZCT assessment methods applicable to the case study. If there are any methods with multiple data inputs, these methods should be populated into Tables 5 and 6.

5.3.3. Step 3 - Ranking, weighting and scoring of Input data sources

This step covers scoring the Input data sources for all methods with multiple data inputs, using Tables 5 and 6. Whilst a subsidiary step of the overall framework, it makes logical sense to perform this scoring first as it produces scores which feed into the subsequent steps.

Data sources for each method need to be defined, ranked in order of importance (relevant to producing demand or LZCT assessment data) and then weighted according to their ranking using the ROD weights in Table 11. Then, each data source needs to be scored for each method for performance against the “Input data integrity” sub-criteria and “Input data resolution” criterion.

Overall weighted scores can then be calculated and input as the score against the relevant “data input integrity” sub-criteria in Tables 7 and 8 for demand and LZCT assessment methods, respectively, and against the “Input data resolution” criterion in Tables 9 and 10 for demand and LZCT assessment methods, respectively. All scoring should take place using the scoring guidelines laid out in Table 3.

It is noted that the “data measurement period” sub-criterion will not be relevant against all data input sources for all methods, e.g. spatial measurements and physical properties. Such input data sources will therefore not be scored against the “Data measurement period” sub-criterion; rather the remaining relevant input data sources will be ranked, weighted and scored against the “Data measurement period” sub-criterion.

Table 5 - Demand Assessment Method Input data source ranking, weighting and scoring

Demand Assessment Method Input data source ranking, weighting and scoring				
Input data source	**Input data source 1**	**Input data source 2**	**Input data source n**	**Overall weighted score**
Ranking	**Input data source 1 rank (decision maker to decide)**	**Input data source 2 rank (decision maker to decide)**	**Input data source n rank (decision maker to decide)**	

Weighting	**Input data source 1 weight (from Table 11)**	**Input data source 2 weight (from Table 11)**	**Input data source n weight (from Table 11)**	
“Data measurement period” score for Demand assessment method n	Input data source 1 score on performance against “data measurement period” sub-criterion	Input data source 2 score on performance against “data measurement period” sub-criterion	Input data source n score on performance against “data measurement period” sub-criterion	Overall weighted score to be input as score for demand assessment method n “data measurement period” sub-criterion in Table 7
“Data accuracy” score for Demand assessment method n	Input data source 1 score on performance against “data accuracy” sub-criterion	Input data source 2 score on performance against “data accuracy” sub-criterion	Input data source n score on performance against “data accuracy” sub-criterion	Overall weighted score to be input as score for demand assessment method n “data accuracy” sub-criterion in Table 7
“Data reliability” score for Demand assessment method n	Input data source 1 score on performance against “data reliability” sub-criterion	Input data source 2 score on performance against “data reliability” sub-criterion	Input data source n score on performance against “data reliability” sub-criterion	Overall weighted score to be input as score for demand assessment method n

				"data reliability" sub-criterion in Table 7
"Input data resolution" score for Demand assessment method n	Input data source 1 score on performance against "input data resolution " criterion	Input data source 2 score on performance against "input data resolution " criterion	Input data source n score on performance against "input data resolution " criterion	Overall weighted score to be input as score for demand assessment method n "input data resolution" criterion in Table 9

Table 6 - LZCT Assessment Method Input data sources ranking, weighting and scoring

LZCT Assessment Method Input data sources ranking, weighting and scoring				
Input data source	**Input data source 1**	**Input data source 2**	**Input data source n**	**Overall weighted score**
Ranking	**Input data source 1 rank (decision maker to decide)**	**Input data source 2 rank (decision maker to decide)**	**Input data source n rank (decision maker to decide)**	
Weighting	**Input data source 1 weight (from Table 11)**	**Input data source 2 weight (from Table 11)**	**Input data source n weight (from Table 11)**	
"Data measurement period" score for LZCT assessment	Input data source 1 score on performance against "data measurement period" sub-criterion	Input data source 2 score on performance against "data measurement period" sub-criterion	Input data source n score on performance against "data measurement period" sub-criterion	Overall weighted score to be input as score for LZCT

method n				assessment method n “data measurement period” sub-criterion in Table 8
“Data accuracy” score for LZCT assessment method n	Input data source 1 score on performance against “data accuracy” sub-criterion	Input data source 2 score on performance against “data accuracy” sub-criterion	Input data source n score on performance against “data accuracy” sub-criterion	Overall weighted score to be input as score for LZCT assessment method n “data accuracy” sub-criterion in Table 8
“Data reliability” LZCT assessment method n	Input data source 1 score on performance against “data reliability” sub-criterion	Input data source 2 score on performance against “data reliability” sub-criterion	Input data source n score on performance against “data reliability” sub-criterion	Overall weighted score to be input as score for LZCT assessment method n “data reliability” sub-criterion in Table 8
“Input data resolution” LZCT assessment	Input data source 1 score on performance against “input data	Input data source 2 score on performance against “input data	Input data source 3 score on performance against “input data	Overall weighted score to be input as score

method n	resolution ” criterion	resolution ” criterion	resolution ” criterion	for LZCT assessment method n “input data resolution” criterion in Table 10

5.3.4. Step 4 - Ranking, weighting and scoring of “Input data integrity” sub-criteria

Next, the “Input data integrity” sub-criteria need to be considered, using Tables 7 and 8. Again, whilst subsidiary step of the overall framework, it makes logical sense to perform this step next as it produces scores which feed into subsequent steps.

The sub-criteria need to first be ranked in order of importance and assigned ROD weights according to Table 11. Then, these sub-criteria need to be scored for each method against the guidelines outlined in Table 3 in Section 5.2.2. Some of these sub-criteria may have scores already input from Tables 5 and 6 from the previous step; these do not need to be re-considered. Overall weighted scores can then be calculated to gain an “Input data integrity” score for each method; these are to be input into Tables 9 and 10 for demand and LZCT assessment methods, respectively.

Table 7 - Demand Assessment Method “Input data integrity” sub-criteria weighting and scoring

Demand Assessment Method “Input data integrity” sub-criteria weighting and scoring				
Sub-criteria	**Data measurement period**	**Data accuracy**	**Data reliability**	**Overall weighted score**

Ranking	**Sub-criteria rank (decision maker to decide)**	**Sub-criteria rank (decision maker to decide)**	**Sub-criteria rank (decision maker to decide)**	
Weighting	**Sub-criteria weight for 3 criteria (from Table 11)**	**Sub-criteria weight for 3 criteria(from Table 11)**	**Sub-criteria weight for 3 criteria (from Table 11)**	
Demand Assessment Method n	Sub-criterion score (based on Table 3 guidelines) OR score from Table 5 (if method has multiple input sources)	Sub-criterion score (based on Table 3 guidelines) OR score from Table 5 (if method has multiple input sources)	Sub-criterion score (based on Table 3 guidelines) OR score from Table 5 (if method has multiple input sources)	Overall weighted score to be input as score for demand assessment method n “Input data integrity” criterion in Table 9

Table 8 - LZCT assessment method “Input data integrity” sub-criteria weighting and scoring

LZCT Assessment Method “Input data integrity” sub-criteria weighting and scoring				
Sub-criteria	**Data measurement period**	**Data accuracy**	**Data reliability**	**Overall weighted score**
Ranking	**Sub-criteria rank (decision maker to decide)**	**Sub-criteria rank (decision maker to decide)**	**Sub-criteria rank (decision maker to decide)**	
Weighting	**Sub-criteria weight for 3 criteria (from Table 11)**	**Sub-criteria weight for 3 criteria(from Table 11)**	**Sub-criteria weight for 3 criteria (from Table 11)**	

LZCT assessment method n	Sub-criterion score (based on Table 3 guidelines) OR score from Table 6 (if method has multiple input sources)	Sub-criterion score (based on Table 3 guidelines) OR score from Table 6 (if method has multiple input sources)	Sub-criterion score (based on Table 3 guidelines) OR score from Table 6 (if method has multiple input sources)	Overall weighted score to be input as score LZCT assessment method n “Input data integrity” criterion in Table 10

5.3.5. Step 5 - Ranking, weighting and scoring of criteria

Next, the criteria in both Table 9 and 10 then need to be ranked in order of importance with respect to the case study. Once this ranking has been performed, ROD weights are be assigned to all criteria using Table 11. All methods then need to be scored against all criteria using the scoring guidelines laid out in Tables 1, 3 and 4 in Section 5.2. It is noted here that “Output suitability” is an essential criterion and therefore any method which does not provide an output of at least hourly resolution will be discounted for use without mitigation through combination with other methods. In a similar vein, any method scoring zero on any other criteria should not be used without mitigation, and method with a low (25) score on any criteria should be used with caution unless remedial steps are taken.

An overall weighted score for all methods can be calculated by multiplying method criteria scores by their respective weights and adding these together; these scores are examined in Step 6.

Table 9 - MCDM table for selection of Demand Assessment Methods

Scoring of Demand Assessment Methods for a Community Energy System								
Demand Assessment Methods		**Method quality criteria**		**Input data criteria**		**Practical considerations criteria**		**Overall weighted score**
		Method validity	**Output suitability**	**Input data resolution**	**Input data integrity**	**Process clarity**	**Requirement for resources**	
	Criteria rank =	Criterion rank (1-6, decision maker to decide)	Criterion rank (1-6, decision maker to decide)	Criterion rank (1-6, decision maker to decide)	Criterion rank (1-6, decision maker to decide)	Criterion rank (1-6, decision maker to decide)	Criterion rank (1-6, decision maker to decide)	
	Criteria weight =	Criterion weight (from Table 11)	Criterion weight (from Table 11)	Criterion weight (from Table 11)	Criterion weight (from Table 11)	Criterion weight (from Table 11)	Criterion weight (from Table 11)	
Demand Assessment Method n		Criterion score (based on Table 1 guidelines)	Criterion score (based on Table 1 guidelines)	Criterion score (based on Table 3 guidelines) OR score from Table 5 (if method has	Criterion score (based on Table 3 guidelines) OR score from Table 7 (if method has	Criterion score (based on Table 4 guidelines)	Criterion score (based on Table 4 guidelines)	Overall weighted scored

				multiple input sources)	multiple input sources)			

Table 10 - MCDM table for selection of LZCT Assessment Methods

Scoring of LZCT Assessment Methods for a Community Energy System								
LZCT Assessment Methods		**Method quality criteria**		**Input data criteria**		**Practical considerations criteria**		**Overall weighted score**
		Method validity	**Output suitability**	**Input data resolution**	**Input data integrity**	**Process clarity**	**Requirement for resources**	
	Criteria rank =	Criterion rank (1-6, decision maker to decide)	Criterion rank (1-6, decision maker to decide)	Criterion rank (1-6, decision maker to decide)	Criterion rank (1-6, decision maker to decide)	Criterion rank (1-6, decision maker to decide)	Criterion rank (1-6, decision maker to decide)	
	Criteria weight =	Criterion weight (from Table 11)	Criterion weight (from Table 11)	Criterion weight (from Table 11)	Criterion weight (from Table 11)	Criterion weight (from Table 11)	Criterion weight (from Table 11)	
LZCT Assessment		Criterion score (based	Criterion score (based	Criterion score (based on Table	Criterion score (based on Table	Criterion score (based on Table	Criterion score (based on Table	Overall weighted

Method n		on Table 1 guidelines)	on Table 1 guidelines)	3 guidelines) OR score from Table 6 (if method has multiple input sources)	3 guidelines) OR score from Table 8 (if method has multiple input sources)	4 guidelines)	4 guidelines)	scored

Table 11 - ROD weights for up to 8 criteria (from [187])

	Number of criteria						
Rank	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0.6932	0.5232	0.418	0.3471	0.2966	0.259	0.2292
2	0.3068	0.324	0.2986	0.2686	0.241	0.2174	0.1977
3		0.1528	0.1912	0.1955	0.1884	0.1781	0.1672
4			0.0922	0.1269	0.1387	0.1406	0.1375
5				0.0619	0.0908	0.1038	0.1084
6					0.0445	0.0679	0.0805
7						0.0334	0.0531
8							0.0263

5.3.6. *Step 6 - Identification most appropriate methods or syntheses of methods*

This step examines the individual criteria and overall weighted scores of all methods in order to identify appropriate methods or combinations of methods for use.

Any method receiving a zero any one criterion cannot be used in isolation, and any methods receiving a low score on any criteria should be used with caution; in such cases mitigation through a synthesis of methods should be sought. Combinations of methods should be sought even if it appears that there are methods which score well enough to be used alone; there may be a higher-scoring synthesis available.

Combinations of methods are scored following the same procedure as for individual methods. The most appropriate method or combination of methods for demand and LZCT assessment will be those receiving the highest score according to these frameworks.

This procedure shall be carried out to demonstrate the frameworks though application to a case study in Chapters 6 and 7.

5.4. Chapter 5 conclusion

The aims of this chapter were to define frameworks for the selection of the most appropriate demand and LZCT assessment methods for CES analysis. This was to be done by defining frameworks based upon the COTSSSP and SMARTER MCDM technique through (i) defining criteria used to judge methods, (ii) defining a scoring system, and (iii) defining scoring guidelines for frameworks.

This has been achieved through consultation with experts and the subsequent definition of criteria under the themes of “Method quality”, “Input data” and “Practical considerations”. Scoring guidelines were defined to ensure a consistent approach to the use of the frameworks. Frameworks based on the COTSSSP and SMARTER MCDM techniques were defined around these criteria, using tables incorporating criteria, sub-criteria and input data sources.

These developed frameworks provide an intuitive, clear and logical step-wise process for the decision-maker to select the most appropriate demand and LZCT assessment methods for CES analysis and to provide input to modelling tools. In addition they provide a platform to identify shortcomings of methods and the subsequent combination of methods to create complementary syntheses of methods to mitigate these shortcomings. A demonstration of the frameworks through application to a case study is shown in Chapters 6 and 7.

6. Chapter 6 - Demonstration of COTSSSP/SMARTER MCDM Demand Assessment Method Selection Framework through Application to a Case Study

6.1. Chapter 6 introduction

The aim of this chapter is to demonstrate the use of the demand assessment method selection framework through application to a case study of a CES on the Isle of Eigg in Scotland.

As per the description of the framework in Chapter 5, the framework is to be implemented by undertaking the following steps:

- Step 1 - identification of decision makers and requirements of decision-making process
- Step 2 - Population of tables with demand assessment methods
- Step 3- Ranking, weighting and scoring of Input data sources
- Step 4 - Ranking, weighting and scoring of "Input data integrity" sub-criteria
- Step 5 - Ranking, weighting and scoring of criteria
- Step 6 - Identification of possible syntheses of methods and selection of demand assessment methods for use in case study

This section is simply a demonstration of the framework; therefore only demands of heat and electricity will be included. If the framework is to be applied in reality, as many demands as possible should be considered; the method list for their analysis should be as exhaustive as possible, being populated via extensive literature review and consultation with energy consultants or experts.

6.2. Step 1 - Identification of decision-makers and requirements of decision-making process

The Community Agent (CA) for this case study was The Isle of Eigg Heritage Trust, which organised and commissioned the work into a CES. The group was made up of islanders who wished to develop a CES because the island was not connected to the electricity grid; households relied on diesel generators with intermittent deliveries of fuel. The primary motivation for a CES was a secure, reliable, affordable energy supply; the Isle of Eigg Heritage Trust was tasked with providing this for the community [3], [188]–[190]. Additionally there was considerable expertise available within the community, and funding made available to explore options.

The decision makers in applying the framework would be the Technical Expert (TE), acting with the CA's motivations in mind. The requirements of the decision-making process are to select the most appropriate assessment method or combination of methods for each demand and LZCT, so that they can then be used to generate inputs for modelling a CES for the case study.

These motivations and requirements shall be considered in ranking and scoring the criteria.

6.3. Step 2 - Population of tables with Demand Assessment Methods for case study

For the purposes of demonstrating the use of the demand assessment method framework, the tables shall be populated with various examples of different types of demand assessment methods introduced in Chapter 2; these were:

Heat demand assessment methods:

- The Scotland Heat Map [44], [45]
- The Reduced Data Standard Assessment Procedure(RdSAP,[46])
- The Passivhaus Planning Package (PHPP, [49])
- Hybrid Optimisation of Multiple Energy Resources (HOMER, [50])
- Generic profiles from The University of Strathclyde's Energy Systems Research Unit (ESRU) [51] [52].
- The ESP-r building energy simulation tool [57]
- Local data gathering

Electrical demand assessment methods:

- The UK ELEXON [61] generic profiles library
- The domestic electricity demand model by Richardson et. al. [62]

- PHPP
- HOMER
- Local data gathering

These methods are shown in Tables 12-28. The process of applying the demand assessment selection framework shall be methodically documented in the following sections, including rationale behind ranking of criteria and scoring of methods based on performance on these criteria.

6.4. Step 3 - Ranking, weighting and scoring of applicable Demand Assessment Methods on Input data sources for case study

A number of the exemplar demand assessment methods require input data from multiple sources to generate heat demand information; the Scotland heat map requires a user input area and uses multiple demand data sources from within the given area to generate annual demand; PHPP, RdSAP and ESP-r utilise physical surveys and climate data; HOMER, ESRU and Elexon utilise generic profiles generated from measured data or datasets which can be scaled based on locally-available data. Based upon these inputs, Input data sources must be defined, ranked and weighted. The “Input data integrity” sub-criteria and the “Input data resolution” criterion must then be scored against these Input data sources; this is outlined below for all relevant demand assessment methods.

6.4.1. Input data sources for heat Demand Assessment Methods - Scotland Heat Map

The Scotland Heat Map requires two inputs; the user must input the location and geographical area to be considered, from which the method draws upon a range of different locally available demand data sources to generate an annual heat demand for the area. From these, “Location and area data” and “Locally available demand data” were extracted as the Input data sources. The “Locally available demand data” was deemed the more important Input data source here, as this the main output from the method.

Under the “Data measurement period” sub-criterion, “Location and area data” were not applicable as it is a spatial input rather than temporal; therefore “Locally available demand data” received 100% of the weighting when scored against this sub-criterion. It was scored 25 as the data from the Scotland Heat Map comes from a variety of sources including billing data (covering a variety of time periods), EPCs (which calculate demand based on building measurements and multi-year climate datasets) and demand data estimated from building footprint and multi-year climate data. However, as it cannot be determined specifically which demand data has been used to gain the annual demand for the user-selected area, a conservative low score of 25 was selected.

The “Location and area data” Input data source scored 100 against the “Data accuracy” sub-criterion; the user-selected area conforms to a 50m grid and demands within the user-selected area will be included. The “Locally available demand data” Input data source scored 50 against the “Data accuracy” sub-criterion; this is because the demand data comes from a variety of sources – some being as basic as estimation of heat demand based on building footprint and others being as accurate as multi-year billing data. As it was not possible to ascertain which specific sources are used to gain heat demand for an area, this intermediate score of was selected.

The “Location and area data” Input data source scored 100 against the “Data reliability” sub-criterion; the user-selected area conforms to a 50m grid and demands within the user-selected area will be included. The “Locally available demand data” Input data source also scored 100 against the “Data reliability” sub-criterion as all available data is measured on-site by either energy consultants (who perform EPC surveys), energy companies (who provide billing data), or by energy consultants (who estimate building heat demand based on footprint).

The “Location and area data” Input data source was scored 50 against the “Input resolution” criterion as a 50m grid is generally a high enough resolution to capture a community’s area, but for assessment of individual buildings or dwellings may prove difficult. The “Locally available demand data” Input data source was scored 25 against “Input resolution” criterion; a low score was chosen due to being unable to know which type of data is used to generate the heat demand for the selected area.

These ranks, weights and scores are for the Scotland Heat Map are shown in Table 12.

Table 12 - Input data source ranking, weighting and scoring for Scotland Heat Map heat Demand Assessment Method

Input data source ranking, weighting and scoring for Scotland Heat Map heat Demand Assessment Method			
Input data source	**Location and area data**	**Locally available demand data**	**Overall weighted score**
Ranking	2	1	
Weighting	0.3068	0.6932	
“Data measurement period” sub-criterion score	n/a	25	25
“Data accuracy” sub-criterion score	100	50	84.7
“Data reliability” sub-criterion score	100	100	100
“Input data resolution” criterion score	50	25	42.3

6.4.2. Input data sources for heat Demand Assessment Methods - PHPP, RdSAP and ESP-r

PHPP, Rd-SAP and ESP-r generate demand profiles based on input from physical surveys of the buildings they analyse and climate data. From this, two Input data sources; “Survey data” and “Climate data” were selected. For all of these assessments, the “Survey data” Input data source was ranked above climate data, as the final demand profiles created will depend more on the dimensions and building fabric than the climate.

For all methods, the “Climate data” Input data source received 100% of the weighting when scoring the “Data measurement period” sub-criterion, as the survey data is not temporal. All methods scored 100 for this as they draw from multi-year climate datasets.

For all methods, the “Survey data” Input data source scored 75 against the “Data accuracy” sub-criterion as it was assumed that a team of trained researchers would be available to gather the required data, but that there may be some issues in gathering it. For all methods, the “Climate data” Input data source scored 75 against the “Data accuracy” sub-criterion as climate data measured from global datasets is available. Whilst this is not measured on-site and thus will not take into account local anomalies, air temperature is the driving factor behind heating demand – this is less likely to be affected by local anomalies.

For all methods, the “Survey data” Input data source was scored 100 against the “Data reliability” sub-criterion, as the survey data would be collected in-site by experts and would be verifiable. All methods scored 100 for the “climate data” Input data source against the “data reliability” sub-criterion as they all draw from reliable, verified datasets from e.g., The Met Office, NASA and the US Department of Energy.

For the “Survey data” Input data source, PHPP and ESP-r scored 100 against the “Input data resolution” criterion, as they both require very high resolution (as low as mm) spatial measurements including building dimensions and material thicknesses, as well as material properties including U-values. Rd-SAP scored 75 against this as it requires less detailed input. PHPP and Rd-SAP scored 50 for the “climate data” Input data source against the “Input data resolution” criterion as they use climate data with a monthly resolution; ESP-r scored 100 as it uses climate data with an hourly profile.

This ranking and scoring for is shown below in Tables 13, 14 and 15 for PHPP, RdSAP and ESP-r, respectively.

Table 13 - Input data source ranking, weighting and scoring for PHPP heat Demand Assessment Method

Input data source ranking, weighting and scoring for PHPP Heat Demand Assessment Method			
Input data source	Survey data	Climate data	Overall weighted score
Ranking	1	2	
Weighting	0.6932	0.3068	
"Data measurement period" sub-criterion score	n/a	100	100
"Data accuracy" sub-criterion score	75	75	75
"Data reliability" sub-criterion score	100	100	100
"Input data resolution" criterion score	100	50	84.7

Table 14 - Input data source ranking, weighting and scoring for RdSAP heat Demand Assessment Method

Input data source ranking, weighting and scoring for RdSAP Heat Demand Assessment Method			
Input data source	Survey data	Climate data	Overall weighted score
Ranking	1	2	
Weighting	0.6932	0.3068	
"Data measurement period" sub-criterion score	n/a	100	100
"Data accuracy" sub-criterion score	75	75	75
"Data reliability" sub-criterion score	100	100	100
RdSAP input data resolution criterion score	75	50	67.3

Table 15 - Input data source ranking, weighting and scoring for ESP-r heat Demand Assessment Method

Input data source ranking, weighting and scoring for ESP-r heat Demand Assessment Method			
Input data source	**Survey data**	**Climate data**	**Overall weighted score**
Ranking	1	2	
Weighting	0.6932	0.3068	
“Data measurement period” sub-criterion score	n/a	100	100
“Data accuracy” sub-criterion score	75	75	75
“Data reliability” sub-criterion score	100	100	100
“Input data resolution” criterion score	100	100	100

6.4.3. Input data sources for heat Demand Assessment Methods – HOMER and ESRU Generic Profiles

HOMER and the ESRU Generic Profiles both generate a heat demand profile based upon generic profiles which can be scaled; from this two Input data sources; “Generic profile data” and “Profile scaling data” were extracted. “Profile scaling data” was deemed the more important Input data source as locally-available data is far more valuable in generating demand data than generic data.

For HOMER, generic profiles are either available from the HOMER synthetic profiles or the Open Energy Information database; only validated data with reference sources is available on this platform, and is available up to hourly resolution. Alternatively the user can upload a demand profile. For ESRU, generic profiles were generated for a range of building types based on measured data at an hourly resolution. These profiles are then scaled, if required, based on available locally-gathered data. For the case study, this data came from the “Small

Isles Energy Audit” [191], which gathered information through interviews and fuel purchase records.

The “Generic profile data” Input data source scored 100 against the “Data measurement period” sub-criterion for both HOMER and ESRU as the data used to construct the generic profiles is multi-year. For the “Profile scaling data” Input data source, HOMER and ESRU both scored 75 against the “Data measurement period” sub-criterion, as energy audit data used to scale profiles from both methods covers only one year and so may not cover annual fluctuations in demand due to climate.

The “Generic profile data” Input data source scored 25 for both HOMER and ESRU against the “Data accuracy” sub-criterion as the methods does not utilise on-site measured data. For HOMER, it cannot be ascertained if the generic profiles available are in any way similar to the demands of the buildings or community on Eigg. Likewise the ESRU method draws from a small dataset of houses to create the generic profiles it uses, and the vast majority of these are in England and will have different demands for those found on Eigg. HOMER and ESRU both scored 75 for the “Profile scaling data” Input data source against the “Data accuracy” sub-criterion against as the data was assumed to be measured on-site by consultants, but that there may be some issues in data collections.

The “Generic profile data” Input data source scored 100 for both HOMER and ESRU against the “Data reliability” sub-criterion as the data comes from validated, well-referenced sources. HOMER and ESRU both scored 100 for the “Profile scaling data” Input data source against the “Data reliability” sub-criterion as the data was assumed to be measured on-site by consultants, and it would be verifiable.

The “Generic profile data” Input data source scored 100 for both HOMER and ESRU against as the “Input data resolution” criterion as data used to create the profiles is at an hourly resolution. The “Profile scaling data” Input data source scored 25 for both HOMER and ESRU against the “Input data resolution” criterion as the resolution of the data used to produce the annual demand in the Small Isles Energy Audit was unknown; it is documented that billing data, fuel purchase records and interviews were conducted to gain this information but resolution is not explicitly documented. Therefore a conservative low score of 25 was selected.

This ranking, weighting and scoring is shown below in Tables 16 and 17.

Table 16 - Input data source scoring, ranking and weighting for HOMER heat Demand Assessment Method

Input data source scoring, ranking and weighting for HOMER heat Demand Assessment Method			
Input data source	**Generic profile data**	**Profile scaling data**	**Overall weighted score**
Ranking	2	1	
Weighting	0.3068	0.6932	
“Data measurement period” sub-criterion score	100	75	92.3
“Data accuracy” sub-criterion score	25	75	40.3
“Data reliability” sub-criterion score	100	100	100
“Input data resolution” criterion score	100	25	77

Table 17 - Input data source ranking, weighting and scoring for ESRU Generic profiles heat demand assessment

Input data source ranking, weighting and scoring for ESRU Generic profiles heat Demand Assessment Method			
Input data source	**Generic profile data**	**Profile scaling data**	**Overall weighted score**
Ranking	2	1	
Weighting	0.3068	0.6932	

“Data measurement period” sub-criterion score	100	75	92.3
“Data accuracy” sub-criterion score	25	75	40.3
“Data reliability” sub-criterion score	100	100	100
“Input data resolution” criterion score	100	25	77

6.4.4. Input data sources for heat Demand Assessment Methods – Local Data Gathering

For the case study, Input data sources for Local Data Gathering came from a single source for heat demand; fuel purchase records from the Small Isles Energy Audit [191]. As there are not multiple input data sources, Local data gathering shall be covered in Step 4.

6.4.5. Input data sources for electrical Demand Assessment Methods – HOMER and Elexon Load Profiling

HOMER and Elexon both utilise generic electrical demand profiles which can be scaled based on locally measured data; from this two Input data sources; “Generic profile data” and “Profile scaling data” were extracted. “Profile scaling data” was deemed the more important Input data source as locally-available data is far more valuable in generating demand data than generic data.

For HOMER, generic profiles are either available from the HOMER synthetic profiles or the Open Energy Information database; only validated data with reference sources is available on this platform, and is available up to hourly resolution. Alternatively the user can upload a demand profile. For ELEXON, generic profiles were generated for a range of profile classes based on user energy consumption. These profiles are then scaled, if required, based on available locally-gathered data. For the case study, this data came from Eigg Electric; the energy company set up on Eigg to operate the CES. Electricity is paid for in advance and a record taken of the date on which a certain value of electricity was bought by a given customer; this gives household electrical consumption with a roughly monthly resolution.

For both HOMER and Elexon, the “Generic profile data” Input data source was scored 100 against the “Data measurement period” sub-criterion as they both use multi-year data to generate their generic profiles. HOMER and Elexon both received a score of 75 on the “Profile scaling data” Input data source against the “Data measurement period” sub-criterion as electricity data was available for one year, and whilst useful would not cover annual fluctuations in demand due to climate or change in island population (electricity demand fluctuates less than heat demand due to climate and thus scored higher here than for the heat demand assessment methods which also utilise annual data for profile scaling).

The “Generic profile data” Input data source scored 50 for both HOMER and Elexon against the “Data accuracy” sub-criterion as whilst neither method utilises on-site measured data, generic profiles for several building types are available, of which types similar to those found on Eigg can be extracted. HOMER and Elexon both scored 75 for the “Profile scaling data” Input data source against the “Data accuracy” sub-criterion as it was assumed that data would be measured on-site by consultants, but that there may be issues with data collection.

The “Generic profile data” Input data source scored 100 for both HOMER and Elexon against the “Data reliability” sub-criterion as the data comes from validated, well-referenced sources. HOMER and Elexon both scored 100 for the “Profile scaling data” Input data source against the “Data reliability” sub-criterion as the data was assumed to be measured on-site by consultants and verifiable.

The “Generic profile data” Input data source scored 100 for HOMER and Elexon against the “Input data resolution” criterion as data used to create the profiles is at an hourly resolution. The “Profile scaling data” Input data source scored 50 for both HOMER and ESRU against the “Input data resolution” criterion, as the data is at a monthly resolution.

This ranking, weighting and scoring is shown below in Tables 18 and 19.

Table 18 - Input data source ranking, weighting and scoring for HOMER electrical Demand Assessment Method

Input data source ranking, weighting and scoring for HOMER electrical Demand Assessment Method

Input data source	Generic profile data	Profile scaling data	Overall weighted score
Ranking	2	1	
Weighting	0.3068	0.6932	
“Data measurement period” sub-criterion score	100	75	92.3
“Data accuracy” sub-criterion score	50	75	57.7
“Data reliability” sub-criterion score	100	100	100
“Input data resolution” criterion score	100	50	84.7

Table 19 - Input data source ranking, weighting and scoring for Elexon electrical demand assessment

Input data source ranking, weighting and scoring for Elexon electrical Demand Assessment Method			
Input data source	**Generic profile data**	**Profile scaling data**	**Overall weighted score**
Ranking	2	1	
Weighting	0.3068	0.6932	
“Data measurement period” sub-criterion score	100	75	92.3
“Data accuracy” sub-criterion score	50	75	57.7
“Data reliability” sub-criterion score	100	100	100
“Input data resolution” criterion score	100	50	84.7

6.4.6. Input data sources for electrical Demand Assessment Methods – PHPP

PHPP generates an electrical demand based on two Input data sources; “Survey data” and “Climate data”. The “Survey data” Input data source was ranked above “Climate data”, as the final demand profiles created will depend more on the dimensions and building fabric than the climate.

The “Climate data” Input data source received 100% of the weighting when scoring the “Data measurement period” sub-criterion, as the survey data is not temporal. PHPP scored 100 for this it uses multi-year climate datasets.

The “Survey data” Input data source scored 75 against the “Data accuracy” sub-criterion as it was assumed that a team of trained researchers would be available to gather the required data, but that there may be some issues in data collection. The “Climate data” Input data source scored 75 against the “Data accuracy” sub-criterion as precise climate data is available, measured from global datasets. Whilst this is not measured on-site and thus will not take into account local anomalies, electrical demand is not particularly affected by climate, save for lighting requirements which make up a small proportion of overall electrical demand. In addition, heating demand on Eigg is not satisfied through electricity due to the 5kW/household power consumption limit set to avoid overloading the grid.

The “Survey data” Input data source was scored 100 against the “Data reliability” sub-criterion as the survey data would be collected on-site by experts and would be verifiable. The “Climate data” Input data source scored 100 against the “data reliability” sub-criterion as the climate data is from a reliable, verified dataset from the Met Office which has been ratified by the Passivhaus Institute.

The “Survey data” Input data source scored 100 against the “Input data resolution” criterion as very high resolution (as low as mm) spatial measurements including building dimensions and material thicknesses, as well as material properties including U-values are required. The “Climate data” Input data source scored 50 against the “Input data resolution” criterion as climate data with monthly resolution is used.

This ranking, weighting and scoring is shown below in Table 20.

Table 20 - Input data source ranking, weighting and scoring for PHPP electrical Demand Assessment Method

Input data source ranking, weighting and scoring for PHPP electrical Demand Assessment Method			
Input data source	**Survey data**	**Climate data**	**Overall weighted score**
Ranking	1	2	
Weighting	0.6932	0.3068	
“Data measurement period” sub-criterion score	n/a	100	100
“Data accuracy” sub-criterion score	75	75	75
“Data reliability” sub-criterion score	100	100	100
“Input data resolution” criterion score	100	50	87.7

6.4.7. Input data sources for electrical Demand Assessment Methods – Domestic electricity demand model

The Domestic electricity demand model generates an electrical demand profile based upon occupant activity and appliance use at different times of the day. The generated demand profile has resolution of one minute, and is simulated based on data derived from the UK Time Use Survey [192], which estimates on a 10 minute resolution how likely it is that an occupant is undertaking a certain activity and using a certain appliance at a certain time. Appliances are either randomly assigned to a household or selected manually with information input from household surveys; the number of occupants must also be selected based on household survey data.

From this, two Input data sources were selected; “Appliance use likelihood” and “Survey data”. The “appliance use likelihood” Input data source was deemed the most important as a high-quality electrical demand profile can still be generated from this without any local survey information; the “Survey data” Input data source only provides occupancy and potentially some slight deviation in appliance ownership from the UK norm.

For the “Data measurement period” sub-criterion, as the “Survey data” Input data source is not temporal, the “Appliance use likelihood” Input data source was given 100% of the weighting and scored 100. The data for the Time Use Survey is derived from a comprehensive survey of thousands of households and how they spend their day; this can essentially be seen as the same as having multiple-year data for a smaller number of households.

The “Appliance use likelihood” Input data source scored 50 for the “Data accuracy” sub-criterion as the appliance use is from surveys outwith the community of Eigg. This may be less of an issue if the CES under consideration was in far more of a representative area, e.g. a suburb of a large city. However, the community on Eigg have somewhat different lifestyles and working patterns due to slightly unconventional lifestyles. This makes the need for locally-measured data more important. The “Survey data” Input data source scored 75 against the “Data accuracy” sub-criterion as it was assumed that the data would be gathered on site by consultants but that the may be some issues with the data.

The “Appliance use likelihood” Input data source scored 100 against the “Data reliability” sub-criterion as the source of data is from the Office of National Statistics; this can be considered a reliable source. The “Survey data” Input data source scored 100 against the “Data reliability” sub-criterion as it was assumed that a team of experts would conduct the surveys and the data would be verifiable.

The “Appliance use likelihood” Input data source was scored 100 against the “Input data resolution” criterion as this data is on a 10 minute resolution. The “Survey data” Input data source was also score 100 against the “Input data resolution” criterion as the exact data required is being surveyed i.e. the number and type of appliances and the occupancy of the household.

This ranking, weighting and scoring is shown below in Table 21.

Table 21 - Input data source ranking, weighting and scoring for The Domestic Electricity Demand Model electrical Demand Assessment Method

Input data source ranking, weighting and scoring for The Domestic Electricity Demand Model electrical Demand Assessment Method			
Input data source	**Appliance use likelihood**	**Survey data**	**Overall weighted score**
Ranking	1	2	
Weighting	0.6932	0.3068	
“Data measurement period” sub-criterion score	100	n/a	100
“Data accuracy” sub-criterion score	50	75	57.7
“Data reliability” sub-criterion score	100	100	100
“Input data resolution” criterion score	100	100	100

6.4.8. Input data sources for electrical Demand Assessment Methods – Local Data Gathering

For the case study, Input data sources for Local Data Gathering came from a single source for electrical demand; electricity purchase records from Eigg Electric, the energy company set up to run the CES on the island. As there are not multiple input data sources, Local data gathering shall be covered in Step 4.

6.5. Step 4 - Ranking, weighting and scoring of Demand Assessment Methods on “Input data integrity” sub-criteria for case study

Next, the “Input data integrity” sub-criteria need to be considered. The sub-criteria need to first be ranked in order of importance and assigned ROD weights according to Table 11. For the case study, it was decided that “Data reliability” was the most important sub-criterion, as without the data being verified as high-quality and reliable, it has basically zero value. The second most important sub-criterion was “Data accuracy”, as to have data which captures local demands is also very valuable due to local anomalies. An assessment can still take place, however, using verified and high-quality data from a suitable proxy site or using more general data. Finally, “Data measurement period” was assigned the next most important rank; whilst useful, having multi-year data was not deemed as important as either “Data accuracy” or “Data reliability”, as there are generally methods to extrapolate data to address gaps. Methods then need to be scored against their performance on these sub-criteria.

6.5.1. Scoring of sub-criteria for heat and electrical Demand Assessment Methods

These sub-criteria need to be scored for each method against the guidelines outlined in Table 3 in Section 5.2.2. This is shown in Table 22 for heat demand methods and Table 23 for electrical demand methods. This scoring has already been covered for all heat and electrical demand assessment methods - apart from Local data gathering - in Step 3; the “Overall Weighted Score” from Tables 12-21 simply feed into the relevant cells in Tables 22 and 23.

6.5.1.1. Scoring of sub-criteria for heat Demand Assessment Methods - Local data gathering

The Local data gathering method for heat demand assessment only has one input data source for the case study and so was not covered in Step 3; it must therefore be addressed here. The only pre-existing locally-available data for heat demand for the case study was from the Small Isles Energy Audit [191], which gathered information over a year through interviews and fuel purchase records to provide an overall annual fuel demand for heating.

Local data gathering scored 75 for the “Data measurement period” sub-criteria as gathering the data over a year may not cover annual fluctuations in demand due to climate.

The “Data accuracy” sub-criterion was scored 100 as the data was gathered on-site through verified sources.

Finally, the “Data reliability” sub-criterion was scored 100 as the data was measured on-site by experts.

6.5.1.2. Scoring of sub-criteria for electrical Demand Assessment Methods – Local data gathering

The Local data gathering method for electrical demand assessment only has one input data source for the case study and so was not covered in Step 3; it must therefore be addressed here. The only pre-existing locally-available data for electrical demand for the case study was from electricity purchase records from Eigg Electric, the company set up to administer the CES on the island. Electricity is paid for in advance and a record taken of the date on which a certain value of electricity was bought by a given customer; this gives household electrical consumption with a roughly monthly resolution.

The “Data measurement period” sub-criterion was scored 75 as electricity data was available for one year, and whilst useful would not cover annual fluctuations in demand due to climate or change in island population (electricity demand fluctuates less than heat demand due to climate and thus scored higher here than for the heat demand assessment methods which also utilise annual data for profile scaling).

The “Data accuracy” sub-criterion scored 100 as the data was measured on-site through verified sources.

The “Data reliability” sub-criterion scored 100 as the data was measured on-site by the CES system which was installed by experts.

6.5.2. Input of “Input data integrity” scores for heat and electrical Demand Assessment Methods into tables

The above weights and scores are input to calculate overall weighted scores for “Input data integrity” for each method – this is shown in Tables 22 and 23. These are to be input into Table 5 for demand assessment methods; this will be covered in Step 5.

Table 22 - Input data integrity sub-criteria weighting and scoring for heat Demand Assessment Methods

Input data integrity sub-criteria weighting and scoring for heat Demand Assessment Methods					
Sub-criteria		Data measurement period	Data accuracy	Data reliability	Input data integrity score
Ranking and weighting	Ranking	3	2	1	
	Weighting	0.1528	0.324	0.5232	
Heat demand methods	Local data gathering	75	100	100	96.2
	Scotland heat map	25	84.7	100	83.6
	RdSAP	100	75	100	91.9
	HOMER	92.3	40.3	100	79.5
	PHPP	100	75	100	91.9
	ESRU generic profiles	92.3	40.3	100	79.5
	ESP-r	100	75	100	91.9

Table 23 - Input data integrity sub-criteria weighting and scoring for electrical Demand Assessment Methods

Input data integrity sub-criteria weighting and scoring for electrical Demand Assessment Methods					
Sub-criteria		Data measurement period	Data accuracy	Data reliability	Input data integrity score
Ranking and	Ranking	3	2	1	

weighting	**Weighting**	0.1528	0.324	0.5232	
Electrical demand methods	**Local data gathering**	75	100	100	96.2
	Elexon load profiling	92.3	57.7	100	85.1
	Domestic electricity demand model	100	57.7	100	86.3
	PHPP	100	75	100	91.9
	HOMER	92.3	57.7	100	85.1

6.6. Step 5 - Ranking, weighting and scoring of Demand Assessment Methods on criteria for case study

Next, the criteria in need to be ranked in order of importance with respect to the case study. Once this ranking has been performed, ROD weights are be assigned to all criteria using Table 11; this is shown in Table 24. All methods then need to be scored against all criteria using the scoring guidelines laid out in Tables 1, 3 and 4 in Section 5.2. Steps 3 and 4 have already provided the scores for most methods on the “input data resolution” and “input data integrity” criteria; these will not be covered again in this section. All ranking, weighting and scoring of criteria for methods considered for the case study are captured in Tables 25 and 26 and explained below.

6.6.1. Criteria ranking and weighting

Criteria ranking and assigned weights are shown in Table 24, and explained below:

- Output suitability - Modelling input data is only useful at an hourly resolution or less; as the primary requirement of this decision-making process is to select the most appropriate assessment methods to provide inputs to modelling, this criterion was deemed the most important.

- Method validity – this criterion covers the actual methodology and calculations used within the method, and hence is an extremely important influence in the reliability of any results – slightly less so than “output data resolution”

- Input data integrity – a method may produce hourly data and be formed of a sound methodology with robust, in-depth calculations, but if the input data is of low integrity, there can be little confidence placed in any results obtained from its use. This was considered very important, but below the importance of either “output data resolution” or “Method validity”.

- Input data resolution - This was considered less important, as methods are able to manipulate input data to provide the required resolution of output data. However, the higher the resolution of required input data, the more likely the method is to provide reliable output.

- Process clarity - As it was assumed that the CA would appoint a TE capable of implementing any method; this was not considered particularly important.

- Resource requirement – This was considered the least important criterion as it was assumed that the CA would have sufficient resources to implement almost any method (with some exceptions).

Table 24 - Criteria ranking and weighting for case study

Criteria	Rank	ROD Weight
Output suitability	1	0.2966
Method validity	2	0.241
Input data integrity	3	0.1884
Input data resolution	4	0.1387
Process clarity	5	0.0908
Resource requirement	6	0.0445

6.6.2. Scoring of heat Demand Assessment Methods – Local data gathering

Gathering locally-available heat demand data e.g. census information, energy bills, EPCs etc., in order to gain as much baseline information is an essential aspect of the analysis of a CES and is one of the first steps to be performed by experts whenever a CES is to be implemented. Local data gathering is an industry-standard method for CES analysis and useful as a "reality check" even if the data gathering on its own is not sufficient; while there are various industry and government guidelines available for data gathering (energy auditing) at the building level e.g. [193], for multi-building and CESs the method is very much ad-hoc and not well documented. Available studies state that "existing demand data was gathered" etc., but the process is not formalised. For these reasons, Local data gathering scored 75 for "Method validity".

The data output by the Local data gathering method is at the same resolution as any available data; for the case study this is from the Small Isles Energy Audit [191] and is at an annual resolution; therefore the "Output suitability" criterion scored 0 as it is an "essential" criterion. Higher scores could have been achieved; e.g. if half-hourly bill data had been available for the billing period then a score of 100 would have been awarded.

The resolution of the data used to produce the annual demand in the Small Isles Energy Audit was unknown; it is documented that billing data, fuel purchase records and interviews were conducted to gain this information but resolution is not explicitly documented. Therefore a conservative low score of 25 was selected for "Input data resolution".

"Input data integrity" scored 96.9; this is a score directly input from Table 22 in Step 4 of the framework.

"Process clarity" scored 0 as there is no real formalisation nor structure for this method, rather the user is expected to read reports of examples of local data gathering from e.g. example projects and adapt the method to suit the case study at hand. The implementation is not clear and so this non-performing score was assigned.

"Requirement for resources" scored 100 as it was assumed to be well within the resources of the CA to employ an expert to conduct Local data gathering.

6.6.3. Scoring of heat Demand Assessment Methods – Scotland Heat Map

“Method validity” was scored 100 as the Scotland Heat Map has a very-well documented methodology which makes the best possible use of the available data; the methodology has been validated and is well-referenced.

“Output suitability” scored 0 as the criterion is “essential” and the Scotland Heat Map provides an annual heat demand.

“Input data resolution” and “Input data integrity” scored 40.8 and 87.4, respectively; rationale behind these scores is found in Steps 3 and 4.

“Process clarity” scored 100 as to generate a heat demand simply requires the user to select an area on a map, and is very simple and intuitive.

“Requirement for resources” scored 100 as the implementation of this method would be well within the resources available to the CA.

6.6.4. Scoring of heat Demand Assessment Methods – RdSAP

“Method validity” for RdSAP was scored 100 as the method has in-depth documentation and uses calculations based on national standards. It is used to produce the nationally-recognised EPCs, and there are several studies showing its implementation.

“Output suitability” was scored 0 as RdSAP provides annual output, and this criterion is deemed “essential”.

“Input data resolution” and “Input data integrity” scored 73.9 and 93.5, respectively; the scoring behind these is explained in Steps 3 and 4.

“Process clarity” was scored 100 as RdSAP has a clear, simple-to-follow procedure and several third-party programmes to simplify the process.

“Requirement for resources” scored 75 as to survey and generate annual heat demand for all buildings on Eigg would require not inconsiderable resources.

6.6.5. *Scoring of heat Demand Assessment Methods – HOMER*

HOMER scored 25 for “Method validity” as whilst there is in-depth documentation of HOMER, with documentation of calculations and several case studies, the documentation of the heat demand profile generator is lacking, with little available verification or justification given for method. The author contacted HOMER and was informed that the methodology was formed through experience in analysing CESs but no evidence/documentation of this was available.

“Output suitability” scored 100 as HOMER provides output at hourly resolution.

“Input data resolution” and “Input data integrity” scored 75.5 and 79.7, respectively; this scoring is explained in Steps 3 and 4.

“Process clarity” scored 100 as the generation of heat demand profiles in HOMER is a simple and intuitive process.

“Requirement for resources” scored 100 as the implementation of the method was easily within the assumed capability of the assigned consultants.

6.6.6. *Scoring of heat Demand Assessment Methods – PHPP*

PHPP scored 100 for “Method validity” as the method is very well documented, with calculations based on national standards and is used to verify that buildings are “Passivhaus” – an internationally-recognised classification of energy efficiency. The method has been verified and there are several case studies available showing implementation of the method.

“Output suitability” scored 0, as this criterion is “Essential” and PHPP provides heat demand at monthly resolution.

“Input data resolution” and “Input data integrity” scored 87.7 and 93.5, respectively; these scores are explained in Steps 3 and 4.

Use of the PHPP is through a Microsoft Excel document, within which there are several spreadsheets. Fields requiring inputs are highlighted, and there are several example documents (of, e.g., a certain house type). Documentation is also highly descriptive and provides a walkthrough of the process required to analyse a building using PHPP. PHPP therefore scored 100 for the “Process clarity” criterion.

“Requirement for resources” scored 70 as approximately week of intensive studying is required to learn the basics of the PHPP, and courses are available. To gather the required input data, experts would be required to undertake building surveys to a high degree of accuracy and reliability, which could take up to two weeks. It was considered that the CA would be able to cover these requirements, although they are not insignificant.

6.6.7. *Scoring of heat Demand Assessment Methods – ESRU generic profiles*

“Method validity” scored 25 for ESRU – Whilst the method is well documented, being the result of a thesis at the University of Strathclyde, it is not validated and draws from a very small dataset to generate its generic demand profiles for different building types. There are also no studies showing the method in use.

“Output suitability” scored 100 as the output is at hourly resolution. “Input data resolution” and “Input data integrity” scored 75.5 and 79.7, respectively; explanation of these scores are in Steps 3 and 4.

“Process clarity” scored 25 as the process to be followed is neither explicit nor clear.

“Requirement for resources” scores 100 as to implement would simply need the user to assign a generic profile to each building on Eigg and create a community profile based on the amalgamation of these; this was assumed to be within the capability of any expert assigned by the CA.

6.6.8. *Scoring of heat Demand Assessment Methods – ESP-r*

“Method validity” scored 75 as whilst ESP-r documentation is unclear, there is evidence that the models used within ESP-r are well-founded and validated.

”Output suitability” scored 100 as the output is at an hourly resolution.

“Input data resolution” and “Input data validity” score 100 and 93.5, respectively; these scores are explained in Steps 3 and 4.

“Process clarity” scored 0 as the method is extremely unintuitive to use with insufficient support or documentation available.

“Requirement for resources” scored zero as use of the method would extremely in-depth training and a prohibitively detailed level of input; the use of ESP-r would be beyond the resources available to the CA.

6.6.9. Scoring of electrical Demand Assessment Methods – Local data gathering

Gathering locally-available electrical demand data e.g. census information, energy bills etc. in order to gain as much baseline information is an essential aspect of the analysis of a CES and is one of the first steps to be performed by experts whenever a CES is to be implemented. Local data gathering is an industry-standard method for CES analysis, however, the process is very much ad-hoc and not well documented. Available studies state that “existing demand data was gathered” etc., but the process is not formalised and there is no documentation available. For these reasons, Local data gathering scored 75 for “Method validity”.

The data output by the Local data gathering method is at the same resolution as any available data. For the case study, this data came from Eigg Electric; the energy company set up on Eigg to operate the CES. Electricity is paid for in advance and a record taken of the date on which a certain value of electricity was bought by a given customer; this gives household electrical consumption with a roughly monthly resolution. Therefore “Output suitability” scored 0 as this is an “essential” criterion.

“Input data resolution” and “Input data integrity” scored 50 and 96.2, respectively; these scores are explained in Steps 3 and 4.

“Process clarity” scored 25 as there is no real formalisation nor structure for this method, rather the user is expected to read reports of examples of local data gathering from e.g. example projects and adapt the method to suit the case study at hand. The implementation is not clear and so this low score was assigned.

“Requirement for resources” scored 100 as it is well within the resources of the CA to employ an expert to conduct Local data gathering.

6.6.10. Scoring of electrical Demand Assessment Methods –Elexon Load Profiling

“Method validity” scored 100 for Elexon – the method is well documented, and used as an industry standard for estimating electrical demands.

“Output suitability” scored 100 as the output is at hourly resolution.

“Input data resolution” and “Input data integrity” scored 84.7 and 85.1, respectively; these scores are explained in Steps 3 and 4.

“Process clarity” scored 100 as Elexon provide a step-by-step guide to generating the demand profiles.

“Requirement for resources” scored 100 as to implement would simply need the user to assign a generic profile to each building on Eigg and create a community profile based on the amalgamation of these; this was assumed to be within the capability of any expert assigned by the CA.

6.6.11. Scoring of electrical Demand Assessment Methods – Domestic Electricity Demand Model

“Method validity” scored 100 as the method is well-documented, well-referenced and shown to be statistically accurate.

“Output suitability” scored 100 as the method has resolution of one minute.

“Input data resolution” and “Input data integrity” scored 100 and 86.3, respectively; these scores are explained in Steps 3 and 4.

“Process clarity” scored 90 as the method has a simple, stepwise implementation process which is clear to follow.

“Requirement for resources” scored 90 as the method is freely available, and implementation – including any necessary household surveys – was considered well within the capabilities of any expert assigned by the CA.

6.6.12. Scoring of electrical Demand Assessment Methods – PHPP

PHPP scored 100 for "Method validity" as the method is very well documented, with calculations based on national standards and is used to verify that buildings are "Passivhaus" – an internationally-recognised classification of energy efficiency. The method has been verified and there are several case studies available showing implementation of the method.

"Output suitability" scored 0, as this criterion is "Essential" and PHPP provides electrical demand at monthly resolution.

"Input data resolution" and "Input data integrity" scored 84.7 and 91.9, respectively; these scores are explained in Steps 3 and 4.

Use of the PHPP is through a Microsoft Excel document, within which there are several spreadsheets. Fields requiring inputs are highlighted, and there are several example documents (of, e.g., a certain house type). Documentation is also highly descriptive and provides a walkthrough of the process required to analyse a building using PHPP. PHPP therefore scored 100 for the "Process clarity" criterion.

"Requirement for resources" scored 75 as approximately week of intensive studying is required to learn the basics of the PHPP, and courses are available. To gather the required input data, experts would be required to undertake building surveys to a high degree of accuracy and reliability, which could take up to two weeks. It was considered that the CA would be able to cover these requirements, although they are not insignificant.

6.6.13. Scoring of electrical Demand Assessment Methods – HOMER

HOMER scored 25 for "Method validity" as whilst there is in-depth documentation of HOMER, with documentation of calculations and several case studies, the documentation of the electrical demand profile generator is lacking, with little available verification or justification given for method.

"Output suitability" scored 100 as HOMER provides output at hourly resolution.

"Input data resolution" and "Input data integrity" scored 84.7 and 85.1, respectively; this scoring is explained in Steps 3 and 4.

“Process clarity” scored 100 as the generation of electrical demand profiles in HOMER is a simple and intuitive process.

“Requirement for resources” scored 100 as the implementation of the method was easily within the assumed capability of the assigned experts.

6.6.14. Tabulation of heat and electrical Demand Assessment Methods

Tables 25 and 26 show the criteria ranking, weighting and scoring for all heat and electrical demand assessment methods covered in this chapter. Identification of the most appropriate method or combinations of methods using these tables shall be covered in Step 6.

Table 25 - Scoring of heat Demand Assessment Methods for a Community Energy system on Eigg

Multi Criteria Decision Making table for selection of heat Demand Assessment Methods for a Community Energy System on Eigg								
Heat demand assessment methods		**Method quality criteria**		**Input data criteria**		**Practical considerations criteria**		**Overall weighted score**
		Method validity	Output suitability	Input data resolution	Input data integrity	Process clarity	Requirement for resources	
	Criteria rank =	2	1	4	3	5	6	
	Criteria weight =	0.2410	0.2966	0.1387	0.1884	0.0908	0.0445	
Local data gathering		75	0	25	96.2	0	100	44.1
Scotland Heat Map		100	0	42.3	83.6	100	100	59.2
RdSAP		100	0	67.3	91.9	100	75	63.2
HOMER		25	100	77	779.5	100	100	74.9
PHPP		100	0	84.7	91.9	100	75	65.6
ESRU		25	100	77	79.5	25	100	68.1
ESP-r		75	100	100	91.9	0	0	78.9

Table 26 - Scoring of electrical Demand Assessment Methods for a Community Energy System on Eigg

Multi Criteria Decision Making table for selection of electrical Demand Assessment Methods for a Community Energy System on Eigg								
Electrical demand assessment methods		**Method quality criteria**		**Input data criteria**		**Practical considerations criteria**		**Overall weighted score**
		Method validity	Output suitability	Input data resolution	Input data integrity	Process clarity	Requirement for resources	
	Criteria rank =	2	1	4	3	5	6	
	Criteria weight =	0.2410	0.2966	0.1387	0.1884	0.0908	0.0445	
Local data gathering		75	0	50	96.2	25	100	49.9
Elexon load profiling		100	100	84.7	85.1	100	100	95.1
Domestic electricity demand model		100	100	100	86.3	100	100	97.4
PHPP		100	0	84.7	91.9	100	75	65.6

HOMER		25	100	84.7	85.1	100	100	77

6.7. Step 6 - Identification most appropriate Demand Assessment Methods or syntheses of Demand Assessment Methods for use in case study

This step examines Tables 25 and 26 to identify the most appropriate methods or synthesis of methods which will be used to generate inputs for modelling tools. The use of the table allows the intuitive identification of low/zero scoring criteria and possible combinations of methods which can be applied to mitigate such scores.

6.7.1. Identification most appropriate heat Demand Assessment Methods or syntheses of Demand Assessment Methods

Upon examination of the heat demand assessment methods table (Table 25) it is immediately clear that whilst ESP-r is highest scoring individual method for assessing heat demand, a score of zero is assigned for both “Process clarity” and “Resource requirement”, as the input detail and time required to implement the method are prohibitive. This reflects the fact that this method is not primarily designed for CES design; rather for detailed simulation of individual rooms and buildings.

The most beneficial synthesis of methods was found to be a combination of PHPP, HOMER and Local data gathering. PHPP employs the use of experts to conduct high-resolution surveys of physical properties of building and monthly climate data to produce a monthly heating demand representative of typical behaviour. This method scores zero for “Output resolution” due to this monthly resolution; this can be mitigated for through the complementary use of HOMER which provides an hourly output. The monthly values generated by PHPP can then be used to scale those provided by HOMER; Local data gathering can be used as a base check for any non-typical behaviour or other anomalies. The identification of this synergistic method is shown in Table 27, with criteria scores contributing to the final synergistic method highlighted.

It would be recommended that in the assessment of heat demands for this case study, that this synthesis of methods be used to generate inputs for any CES modelling tool to be used.

Table 27 - Identification of synthesis of heat Demand Assessment Methods for a Community Energy System on Eigg

Identification of syntheses of heat Demand Assessment Methods for a Community Energy System on Eigg								
Heat demand assessment methods		**Method quality criteria**		**Input data criteria**		**Practical considerations criteria**		**Weighted score for options**
		Method validity	Output suitability	Input data resolution	Input data integrity	Process clarity	Requirement for resources	
	Criteria rank =	2	1	4	3	5	6	
	Criteria weight =	0.2410	0.2966	0.1387	0.1884	0.0908	0.0445	
Local data gathering		75	0	25	96.2	0	100	44.1
HOMER		25	100	77	79.5	100	100	74.9
PHPP		100	0	84.7	91.9	100	75	65.6
PHPP + HOMER + Data gathering		100	100	84.7	96.2	100	1000	97.2

6.7.2. Identification most appropriate electrical Demand Assessment Methods or syntheses of electrical Demand Assessment Methods

Upon examination of the electrical demand assessment methods table (Table 26) it is immediately clear that The Domestic Electricity Demand Model appears to be the most appropriate methods to use – in isolation – for the assessment of electricity demand for the case study. The Elexon Load Profiling method also scores similarly. Despite this, the framework recommends that potential syntheses of methods are explored in order to determine if the score can be improved upon. Local data gathering and PHPP both scored 0 for “Output suitability” and would require combination with another method to mitigate this zero score if taken forwards in a synthesis on methods.

The most beneficial synthesis of methods was found to be a combination of PHPP, the Domestic Electricity Demand Model and Local data gathering. PHPP employs the use of experts to conduct high-resolution surveys of physical properties of building and monthly climate data to produce a monthly electrical demand. This method scores zero for “Output resolution” due to this monthly resolution; this can be mitigated for through the complementary use of the Domestic Electricity Demand Model which provides output at resolution of one minute. The monthly values generated by PHPP can then be used to scale those provided by the Domestic Electricity Demand Model. Local data gathering can then be used to verify the results, and scale if required. The identification of this synergistic method is shown in Table 28, with scores contributing to the final synergistic method highlighted.

It would be recommended that in the assessment of electrical demands for this case study, that this synthesis of methods be used to generate inputs for any CES modelling tool to be used.

Table 28 - Identification of synthesis of electrical Demand Assessment Methods for a Community Energy System on Eigg

Identification of synthesis of electrical Demand Assessment Methods for a Community Energy System on Eigg								
Electrical demand assessment methods		**Method quality criteria**		**Input data criteria**		**Practical considerations criteria**		**Overall weighted score**
		Method validity	Output suitability	Input data resolution	Input data integrity	Process clarity	Requirement for resources	
	Criteria rank =	2	1	4	3	5	6	
	Criteria weight =	0.2410	0.2966	0.1387	0.1884	0.0908	0.0445	
Local data gathering		75	0	50	96.2	25	100	49.9
Domestic electricity demand model		100	100	100	86.3	100	100	97.4
PHPP		100	0	87.7	93.5	80	70	64.3
Synergistic combination: PHPP + Domestic Electricity Demand Model + Local data gathering		100	100	100	96.2	100	100	99.3

6.8. Chapter 6 conclusion

The aim of this chapter was to demonstrate the use of the demand assessment method selection framework through application to a case study of a CES on the Isle of Eigg in Scotland. This has been achieved through full application of the steps laid out in the definition of the framework in Chapter 5.

In Step 1 of the framework, the decision-makers and requirements of the decision-making process were identified. This was the Isle of Eigg Heritage Trust, a community body set up to manage community ownership of the island and which is made up of several community members. The requirements of the decision-making process were to select the most appropriate demand assessment methods to be used to assess existing and future energy demand on Eigg so that these could be used in the modelling of a possible CES on Eigg. The motivation behind this was a secure energy supply for the community, and it was assumed that there was sufficient funding to employ experts to undertake any necessary analysis of the CES.

Next, in Step 2 of the framework, several exemplar electrical and heat demand assessment methods were input into the framework tables. As several of these methods require multiple input sources (e.g. from physical surveys and climate data), Step 3 saw the ranking, weighting and scoring of these Input data sources for each applicable method. This provided input to Step 4 which ranked, weighted and scored the “input data integrity” sub-criteria: “Data measurement period”, “data accuracy” and “data reliability”. This in turn provided input to Step 5, which ranked, weighted and scored the primary criteria of “Method validity”, “Output suitability”, “Input data resolution”, “Input data integrity”, “Process Clarity” and “Requirement for resources”. A final weighted score was then obtained through linear addition for each method.

The final step explored the possible combination of methods to create syntheses of methods. For heat demand assessment methods the most beneficial combination was PHPP, HOMER and Local data gathering. For the electrical demand assessment methods, a combination of PHPP, The Domestic Electricity Demand Model and Local data gathering was found to be most beneficial. These syntheses of methods were recommended for the assessment of demands for the case study.

This chapter has successfully demonstrated the use of the demand assessment methods selection framework, which can effectively select the most appropriate demand assessment method for a given situation; based on a series of criteria, and weights which change depending on case-by-case priorities. Due to inherent differences and weaknesses in methods, combinations of methods will often be the most appropriate solution for a case study.

7. Chapter 7 - Demonstration of COTSSSP/SMARTER MCDM LZCT Assessment Method Selection Framework through Application to a Case Study

7.1. Chapter 7 introduction

This section will cover the use of the LZCT assessment method selection framework, following the COTSSSP and SMARTER MCDM framework described in Chapter 5.

In this chapter, the LZCT assessment method selection framework is demonstrated through application to a case study of a CES on the Isle of Eigg in Scotland; this case study was introduced in Chapter 6.

As per the description of the framework in Chapter 5, this will include the following framework implementation steps:

- Step 1 - identification of decision makers and requirements of decision-making process
- Step 2 - Population of tables with LZCT assessment methods
- Step 3- Ranking, weighting and scoring of Input data sources
- Step 4 - Ranking, weighting and scoring of “input data integrity” sub-criteria
- Step 5 - Ranking, weighting and scoring of criteria
- Step 6 - Identification of possible syntheses of methods and selection of LZCT assessment methods for use in case study

This section is simply a demonstration of the framework; therefore only one exemplar LZCT (wind turbines) will be included. If the framework is to be applied in reality, as many LZCTs as possible should be considered; the method list should be as exhaustive as possible and populated via extensive literature review and consultation with energy consultants or experts.

7.2. Step 1 - Identification of decision-makers and requirements of decision-making process

As the case study explored in this chapter is the same as explored in Chapter 6, the same decision-makers and requirement of the decision-making process apply here. The CA is the Isle of Eigg Heritage Trust, which is made up of community members, and motivation behind developing a CES is a secure, reliable energy supply. Considerable expertise was available within the community, and it was assumed that there were sufficient funds available to hire experts to conduct CES analysis (within reason).

7.3. Step 2 - Population of tables with LZCT Assessment Methods for case study

For the purposes of demonstrating the use of the LZCT assessment method selection framework, the tables shall be populated with the various examples of different types of LZCT assessment methods introduced in Section 2.4. From these, the example wind turbine assessment methods examined in this section shall be the following:

- Local data gathering
- Renewables Ninja [73]
- “Wind Resource Assessment: A Practical Guide to Developing a Wind Project” [76]
- A CES modelling tool with embedded supply profile generator; HOMER [79] shall be used as an example of this
- The “CARES Renewable Energy: Wind Module” [33]

7.4. Step 3 - Ranking, weighting and scoring of applicable LZCT Assessment Methods on Input data sources for case study

A number of the exemplar LZCT assessment methods require input data from multiple sources to generate LZCT supply profile information; Renewables Ninja and HOMER require the user to input a location and wind turbine type which is used to generate an annual supply profile based on the climate at that location and turbine specification; “Wind Resource Assessment: A Practical Guide to Developing a Wind Project” requires the user to conduct in-depth site appraisal and select an appropriate wind measurement system (remote sensing systems, wind measurement towers etc.) to gain an annual wind speed profile and perform associated validation on the data; and the "CARES Renewable Energy: Wind Module" provides basic rules of thumb for site selection and wind turbine suitability.

Based upon these inputs, Input data sources must be defined, ranked and weighted. The "Input data integrity" sub-criteria and the "Input data resolution" criterion must then be scored against these Input data sources; this is outlined below for all relevant LZCT assessment methods.

7.4.1. Input data sources for LZCT Assessment Methods – Renewables Ninja

Renewables Ninja utilises 3 inputs. The user must input a location on the map from which Renewables Ninja uses wind speed data for the location in combination with turbine specifications to generate an energy supply profile for one year with a resolution of one hour. From this, three Input data sources were selected; "Wind speed", "Location" and "Turbine specifications". "Wind speed" was deemed to be the most important of these as it is the most important data of these for calculating the potential energy supply profile from a wind turbine. Other factors such as turbulence are also very important but not covered by Renewables Ninja. Second-most important was "location", as there can be many local anomalies which affect wind speed such as landforms, trees, buildings etc. Finally, "Turbine specifications" was deemed the least-important as whilst an energy supply profile clearly cannot be produced without turbine specifications, these are easily and widely available.

Under the "Data measurement period" sub-criterion, the "Location" and "Wind turbine specifications" Input data sources were not applicable as they are not temporal measures. Therefore the "Wind speed" Input data source received 100% of the weight, and was scored 100 as the wind speed is from NASA's "MERRA 2" climate dataset which is based on multi-year measurements.

The "Wind speed" Input data source scored 50 against the "Data accuracy" sub-criterion as the wind speeds for the NASA "MERRA 2" are not measured on site; rather they are measured by satellite. The MERRA 2 dataset was compared to measurements taken at several weather stations across the world, and was shown to have the highest errors at "coastal-land transition zones which are characterised by strong land-sea gradients and discontinuities" [194]. The case study area is located at such a zone and data for this area cannot be relied upon as accurate. The "Location" Input data source scored 50 against the

“Data accuracy” sub-criterion as the spatial resolution of the “MERRA 2“ dataset is at a 50km and so will fail to take account of local landforms etc., which can have a profound effect on wind data at a local level. The “Turbine specifications” Input data source scored 100 against the “Data accuracy” sub-criterion as all of the required data to calculate wind turbine power output according to well-known and industry standard calculations are provided.

The “Wind speed” Input data source scored 100 against the “Data reliability” sub-criterion as the data comes from NASA; a very well-known and reliable body. The MERRA 2 dataset has been extensively used and validated, and is under constant review and improvement. The “Location” Input data source scored 100 against the “Data reliability” sub-criterion as again, the location is from NASA. The “Turbine specifications” Input data source scored 75 against the “Data reliability” sub-criterion as whilst these specifications are directly from the manufacturer, it is unclear how or if these specifications have been verified.

The “Wind speed” Input data source scored 100 against the “Input data resolution” criterion as the data input is at an hourly resolution. The Location Input data source scored 25 against the “Input data resolution” criterion scored as the spatial resolution is 50km. Finally, the “Wind turbine specification” Input data source scored 100 against the “Input data resolution” criterion as the data is at the required level of detail to perform all necessary calculations.

These ranks, weights and scores are for Renewables Ninja are shown in Table 29.

Table 29 - Input data source ranking, weighting and scoring for Renewables Ninja LZCT Assessment Method

Input data source ranking, weighting and scoring for Renewables Ninja LZCT Assessment Method				
Input data sources	**Wind speed**	**Location**	**Turbine specifications**	**Overall weighted score**
Ranking	1	2	3	
Weighting	0.5232	0.324	0.1528	
“Data measurement period” sub-criterion score	100	n/a	n/a	100

“Data accuracy” sub-criterion score	50	50	100	57.6
“Data reliability” sub-criterion score	100	100	75	96.2
“Input data resolution” criterion score	100	25	100	74.1

7.4.2. Input data sources for LZCT Assessment Methods – “Wind Resource Assessment: A Practical Guide to Developing a Wind Project”

“Wind Resource Assessment: A Practical Guide to Developing a Wind Project” [76] s a practical, authoritative guide to undertaking a high-quality assessment of a wind resource for a wind turbine project. It covers site selection, installation and operation of a wind resource monitoring programme; it then covers data quality control, validation and extrapolation and wind flow modelling. The method requires a team of experts to undertake high-resolution wind speed measurement over at least a year; all measurements to be made on-site; and has been documented by a team of energy experts from industry and academia. Therefore, rather than undertake the arduous task of identifying the multiple data inputs required by this method, including subsequent ranking, weighting and the scoring against each sub-criteria against them, it could reasonably be assumed that all data inputs would score very similarly for “Data measurement period”, “Data accuracy”, “Data reliability” and “Input data resolution”. This score would be 100 for all data inputs; this is shown in Table 30.

Table 30 - Input data source ranking, weighting and scoring for the “Wind Resource Assessment: A Practical Guide to Developing a Wind Project” LZCT Assessment Method

Input data source ranking, weighting and scoring for the “Wind Resource Assessment: A Practical Guide to Developing a Wind Project” LZCT Assessment Method		
Input data source	**Multiple inputs**	**Overall weighted score**
Ranking	1	
Weighting	1	

"Data measurement period" sub-criterion score	100	100
"Data accuracy" sub-criterion score	100	100
"Data reliability" sub-criterion score	100	100
"Input data resolution" criterion score	100	100

7.4.3. Input data sources for LZCT Assessment Methods – HOMER

HOMER utilises 3 inputs. First, the user must input a location; HOMER then directly downloads monthly average wind speed data for this location from NASA [195]. HOMER then uses to synthesise hourly wind speeds over a year by applying parameter’s which represent wind behavioural patterns including “strong and sustained gusts, long lulls between windy periods, and seasonal and diurnal patterns”. It is also possible to directly import a wind speed data file, if the user has this data available; the HOMER synthesised hourly wind speed parameters can also be applied to this data if required. Wind speed data is then used in combination with turbine specifications to generate an energy supply profile for one year with a resolution of one hour. From this, three Input data sources were defined; “Wind speed”, “Location” and “Turbine specifications”. “Wind speed” was deemed to be the most important of these as it is overridingly the most important data required for calculating the potential energy supply profile from a wind turbine. Second-most important was “Location”, as there can be many local anomalies which affect wind speed such as landforms, trees, buildings etc. Finally, “Turbine specifications” was deemed the least-important as whilst an energy supply profile clearly cannot be produced without turbine specifications, these are easily and widely available.

Under the “Data measurement period” sub-criterion, the “Location” and “Wind turbine specifications” Input data sources were not applicable as they are not temporal measures. Therefore the “Wind speed” Input data source received 100% of the weight, and was scored 100 as the wind speed is from NASA’s Surface Meteorology and Solar Energy Database for wind speeds, which is based on multi-year measurements.

The “Wind speed” Input data source scored 50 against the “Data accuracy” sub-criterion as the wind speeds for the NASA dataset are not measured on site; rather they are measured by satellite. The “Location” Input data source scored 50 against the “Data accuracy” sub-criterion as the spatial resolution of the dataset is at a 50km and so will fail to take account of local landforms etc., which can have a profound effect on wind data at a local level. The “Turbine specifications” Input data source scored 100 against the “Data accuracy” sub-criterion as all of the required data to calculate wind turbine power output according to well-known and industry standard calculations are provided.

The “Wind speed” Input data source scored 100 against the “Data reliability” sub-criterion as the data comes from NASA; a very well-known and reliable body. The “Location” Input data source scored 100 for the “Data reliability” sub-criterion as again, the location is from NASA. The “Turbine specifications” Input data source scored 75 against the “Data reliability” sub-criterion as whilst these specifications are directly from the manufacturer, it is unclear how or if these specifications have been verified.

The “Wind speed” Input data source scored 50 for the “Input data resolution” criterion as the data input is at monthly resolution. The “Location” Input data source scored 25 for the “Input data resolution” criterion as the spatial resolution is 50km. Finally, the “Wind turbine specification” Input data source scored 100 for the “Input data resolution” criterion as the data is at the required level of detail to perform all necessary calculations.

These ranks, weights and scores are for HOMER are shown in Table 31.

Table 31 - Input data source ranking, weighting and scoring for HOMER LZCT Assessment Method

Input data source ranking, weighting and scoring for HOMER LZCT Assessment Method				
Input data source	**Wind speed**	**Location**	**Turbine specifications**	**Overall weighted score**
Ranking	1	2	3	
Weighting	0.5232	0.324	0.1528	
"Data measurement period" sub-criterion score	100	n/a	n/a	100
"Data accuracy" sub-criterion score	50	50	100	57.6

"Data reliability" sub-criterion score	100	100	75	96.2
"Input data resolution" criterion score	50	25	100	49.5

7.4.4. Input data sources for LZCT Assessment Methods – "CARES Renewable Energy: Wind Module"

The "CARES Renewable Energy: Wind Module" provided by Local Energy Scotland [33] is a general guide to the feasibility of wind turbines in a CES. It includes a general rule of thumb that an annual average wind speed of 6.4 m/s at 45m above ground level is required for small scale turbines. It also includes general site requirements such as topography, location, wind speeds, land use, physical/grid access and ownership. From these, "Wind speed" and "Site selection" were defined as the Input data sources. "Wind speed" was deemed the most important Input data source as wind speed is the most important of these in determining the power output on wind turbines and their feasibility. Other factors such as turbulence are also very important but not covered by the CARES guide.

For the "Data measurement period" sub-criterion, the "Wind speed" Input data source received 100% of the weighting, as "Site selection" is not temporal. "Wind speed" was scored 100 as the dataset suggested is the Department of Energy and Climate Change (DECC) wind speed database [196], which uses multi-year measurements.

"Wind speed" and "Site selection" Input data sources both scored 25 against the "Data accuracy" sub-criterion as the recommended data set is now out of date and archived; the archived dataset specifically states that the data cannot be considered accurate; it can only be considered as very high level data. These low scores were awarded as only very general high-level guidelines on site suitability are provided.

The "Wind speed" Input data source scored 100 against the "Data reliability" sub-criterion as DECC was a well'-known and reliable source of information. The "Site selection" Input data source also scored 100 against the "Data reliability" sub-criterion as Local Energy Scotland is a reliable and well-known source of information. The guidelines for site selection have been used by communities in the implementation of successful projects such as the Sròndoire Wind Farm [197]

The “Wind turbines” Input data source scored 20 against the “Input data resolution” criterion as the DECC data is an annual wind speed. The “Site selection” Input data source also scored 25 against the “Input data resolution” criterion as the guidelines are rough and high level.

These ranks, weights and scores for the “CARES Renewable Energy: Wind Module” are shown in Table 32.

Table 32 - Input data source ranking, weighting and scoring for “CARES Renewable Energy: Wind Module” LZCT Assessment Method

Input data source ranking, weighting and scoring for “CARES Renewable Energy: Wind Module” LZCT Assessment Method			
Input data source	**Wind speed**	**Site selection**	**Overall weighted score**
Ranking	1	2	
Weighting	0.6932	0.3068	
"Data measurement period" sub-criterion score	100	n/a	100
"Data accuracy" sub-criterion score	25	25	25
"Data reliability" sub-criterion score	100	100	100
"Input data resolution" criterion score	25	25	25

7.4.5. Input data sources for LZCT Assessment Methods – Local Data Gathering

For the case study, Input data sources for Local Data Gathering came from a single source for electrical demand; existing wind turbine data for an existing turbine on the island. As there are not multiple input data sources, Local data gathering shall be covered in Step 4.

7.5. Step 4 - Ranking, weighting and scoring of LZCT Assessment Methods on “Input data integrity” sub-criteria for case study

Next, the “Input data integrity” sub-criteria need to be considered. The sub-criteria need to first be ranked in order of importance and assigned ROD weights according to Table 11. For the case study, it was decided that “Data reliability” was the most important sub-criterion, as without the data being verified as high-quality and reliable, it has basically zero value. The second most important sub-criterion was “Data accuracy”, as to have data which captures local information is very valuable due to local anomalies. An assessment can still take place, however, using verified and high-quality data from a suitable proxy site or using more general data. Finally, “Data measurement period” was assigned the next most important rank; whilst useful, having multi-year data was not deemed as important as either “data accuracy” or “Data reliability”, as there are generally methods to extrapolate data to address gaps.

7.5.1. Scoring of sub-criteria for LZCT Assessment Methods

These sub-criteria need to be scored for each method against the guidelines outlined in Table 3 in Section 5; this is shown in Table 33 for LZCT assessment methods. This scoring has already been undertaken for the LZCT assessment methods covered in Step 3; the “Overall Weighted Score” from Tables 29-32 simply feed into the relevant cells in Table 33.

7.5.1.1. Scoring of sub-criteria for LZCT Assessment Methods – Local data gathering

In addition to the methods with multiple data input sources covered in Step 3, the Local data gathering method still needs to be covered. For the case study, data was available in the form of measured wind turbine output data for an existing turbine, which could be used to back-calculate wind speeds based on turbine specifications. This data was available at an hourly resolution and had been measured on-site remotely by the company which installed the existing system. The “Data measurement period” sub-criterion scored 75 as whilst the data was measured over a period of approximately 3 years, there were several gaps in the data of weeks or months. The “Data accuracy” sub-criterion scored 100 as all of the data was measured on-site. “Data reliability” scored 75 as whilst the data was gathered by experts, it was uncertain if this data had been verified. These scores are input into the relevant cells in Table 33.

7.5.2. Input of "Input data integrity" scores for LZCT Assessment Methods into tables

The above ranking, weights and scores are input to gain overall weighted scores for "Input data integrity" for each method; these can be seen in Table 33 and are to be input into Table 6 for LZCT assessment methods. This will be covered in Step 5.

Table 33 - Input data integrity sub-criteria weighting and scoring for LZCT Assessment Methods

Input data integrity sub-criteria weighting and scoring for LZCT Assessment Methods					
Sub-criteria		**Data measurement period**	**Data accuracy**	**Data reliability**	**Input data integrity score**
Ranking and weighting	**Ranking**	3	2	1	
	Weighting	0.1528	0.324	0.5232	
Wind turbine assessment methods	**Local data gathering**	75	100	75	83.1
	Renewables Ninja	100	57.6	96.2	84.3
	"Wind Resource Assessment: A Practical Guide to Developing a Wind Project"	100	100	100	100
	HOMER	100	57.6	96.2	84.3
	"CARES Renewable	100	25	100	75.7

	Energy: Wind Module”				

7.6. Step 5 - Ranking, weighting and scoring LZCT Assessment Methods on criteria for case study

Next, the criteria need to be ranked in order of importance with respect to the case study. Once this ranking has been performed, ROD weights are be assigned to all criteria using Table 11. LZCT assessment method scoring criteria were ranked identically (and for the same reasons) to the demand assessment method scoring criteria; this was covered in Chapter 5 and shall therefore not be covered here.

All LZCT assessment methods then need to be scored against all criteria using the scoring guidelines laid out in Tables 1, 3 and 4 in Chapter 5. Steps 3 and 4 have already provided the scores for most methods on the “input data resolution” and “input data integrity” criteria; these will not be covered again in this section. Scoring of criteria for the case study is captured in Table 34 and is explained below.

7.6.1. Scoring of LZCT Assessment Methods – Local data gathering

If available, gathering locally-available LZCT and resource data – wind speeds, existing wind turbine power output data etc., in order to gain as much baseline information is an essential aspect of the analysis of a CES and is one of the first steps to be performed by experts whenever a CES is to be implemented. Local data gathering is an industry-standard method for CES analysis, however, the method is very much ad-hoc and not well documented or formalised. For these reasons, Local data gathering scored 75 for “Method validity”.

The data output by the Local data gathering method is at the same resolution as any available data; for the case study this is the exiting wind turbine production values, which are at an hourly resolution; therefore the “Output suitability” criterion scored 100.

The resolution of the data used to produce this was hourly; therefore a score of 100 was selected for “Input data resolution”.

“Input data integrity” scored 83.1; this is a score directly input from Table 33 in Step 4 of the framework.

The implementation of the method is not clear and so “Process clarity” scored 25; there is no real formalisation nor structure for this method, rather the user is expected to read reports of examples of Local data gathering from e.g. example projects and adapt the method to suit the case study at hand.

“Requirement for resources” scored 100 as it is well within the resources of the CA to employ an expert to conduct Local data gathering.

7.6.2. Scoring of LZCT Assessment Methods – Renewables Ninja

Renewables Ninja is well-documented, with a methodology using industry-standard calculations to derive power output from wind speeds and turbine specifications. There are also a significant number of publications on the method; these were, however, all written by the method authors. Therefore Renewables Ninja scored 75 for “Method validity”.

“Output suitability scored 100 as the method provides an hourly output.

“Input data resolution and “Input data integrity” scored 75.7 and 84.3; these scores were covered in Steps 3 and 4.

“Process clarity” scored 100 as the method utilised a user-friendly, interface which is intuitive to use.

“Requirement for resources” scored 100 as the method is very quick and simple to use – it was assumed that the CA would have ample resources to employ this method.

7.6.3. Scoring of LZCT Assessment Methods – “Wind Resource Assessment: A Practical Guide to Developing a Wind Project”

“Wind Resource Assessment: A Practical Guide to Developing a Wind Project” is the most in-depth and well-researched guide available on the assessment of the feasibility of wind turbines for a CES. It has been well-referenced and validated and is the authoritative text on the subject. “Method validity” therefore scored 100.

"Output suitability" scored 100 as the method provides output at an hourly resolution.

"Input data resolution and "Input data integrity" each scored 100; these scores are explained in Steps 3 and 4.

"Process clarity" scored 75 as the entire process is rather long and can be complex at times.

"Requirement for resources" scored 0 as the method is extremely thorough and in-depth, and would require large investment to employ a team of experts to implement; this was considered outwith the resources available to the CA.

7.6.4. Scoring of LZCT Assessment Methods – HOMER

HOMER scored 100 for "Method validity" as there is in-depth documentation of HOMER, with documentation of calculations and several case studies. The wind turbine power output calculations are industry standard, utilising wind speeds and wind turbine specifications.

"Output suitability" scored 100 as the output has an hourly resolution.

"Input data resolution" and "Input data integrity" scored 49.5 and 84.3, respectively; these scores are covered in Steps 3 and 4.

"Process clarity" scored 100 as the process is clear and easy to follow.

"Requirement for resources" scored 100 as employing an expert to implement this method was assumed to be within the resources of the CA.

7.6.5. Scoring of LZCT Assessment Methods - "CARES Renewable Energy: Wind Module"

The "CARES Renewable Energy: Wind Module" method scores 25 for "Method validity" as the calculations behind the wind turbine validity are extremely rudimentary and high level, as are the guidelines for site selection.

"Output suitability" scored 0 as the output is a mean annual wind speed.

“Input data resolution” and “Input data integrity” scored 25 and 75.7, respectively; these scores are explained in more depth in Steps 3 and 4.

“Process clarity” scored 75 as the process is generally clear albeit with some dead links and resources.

“Requirement for resources” scored 100 as employing an expert to implement this method was assumed to be within the resources of the CA.

7.6.6. Tabulation of LZCT Assessment Methods

Table 34 shows the criteria ranking, weighting and scoring for all exemplar LZCT assessment methods covered in this chapter. Identification of the most appropriate method or combinations of methods using these tables shall be covered in Step 6.

Table 34 - Scoring of LZCT Assessment Methods for a Community Energy System on Eigg

Multi Criteria Decision Making table for selection of LZCT Assessment Methods for a Community Energy System on Eigg								
Wind turbine assessment methods		**Method quality criteria**		**Data Criteria**		**Practical considerations criteria**		**Weighted score for options**
		Method validity	Output suitability	Input data resolution	Input data integrity	Process clarity	Requirement for resources	
	Criteria rank =	2	1	4	3	5	6	
	Criteria weight =	0.241	0.297	0.139	0.188	0.091	0.045	
Local data gathering		75	100	100	83.1	25	100	84
Renewables Ninja		75	100	75.7	84.3	100	100	87.6
“Wind Resource Assessment: A Practical Guide to Developing a Wind Project”		100	100	100	100.0	75	0	93.3
HOMER		100	100	49.5	84.3	100	100	90
“CARES Renewable Energy: Wind Module”		25	0	25	75.7	75	100	35

7.7. Step 6 - Identification of most appropriate LZCT Assessment Method or syntheses of LZCT Assessment Methods for use in case study

This step examines Table 34 to identify the most appropriate methods or syntheses of LZCT methods which will be used to generate inputs for modelling tools. The use of the table allows the intuitive identification of low/zero scoring criteria and possible combinations of methods which can be applied to mitigate such scores.

Upon examination of the MCDM table for selection of LZCT assessment methods (Table 34), it is clear that the "Wind Resource Assessment: A Practical Guide to Developing a Wind Project" method is the highest-scoring method; however, it received a zero score for the "requirement for resources" criterion as the level of detail in the method meant the requirement for resources for implementation was prohibitive. This zero score cannot be mitigated and thus the method must be discounted.

The Local data gathering, Renewables Ninja and HOMER methods all scored similarly, receiving scores of 84, 87.6 and 90, respectively. The next step would be to identify beneficial syntheses of methods in order to obtain a more appropriate solution.

The most beneficial combination of methods was found to be Renewables Ninja in combination with Local data gathering. The "input data resolution" criterion scored higher for "Data gathering" as the locally-measured wind speed and turbine production data was at an hourly resolution. In addition, the "Input data integrity" criterion scored higher for the Renewables ninja method, due to there being no gaps in the dataset. The combination of these two methods means that the lower score on one method for one criterion can be mitigated by the higher score awarded to the other method. Renewables Ninja can be used to gain a yearly profile with an hourly resolution, and Local data gathering can be used to scale this. The identification of this synergistic method is shown in Table 35, with scores contributing to the final synergistic method highlighted.

It would be recommended that in the assessment of wind turbines for this case study, that this synthesis of methods be used to generate inputs for any CES modelling tool to be used.

Table 35 - Identification of synthesis of LZCT Assessment Methods for a Community Energy System on Eigg

Identification of syntheses of LZCT Assessment Methods for a Community Energy System on Eigg								
Wind turbine assessment methods		**Method quality criteria**		**Data Criteria**		**Practical considerations criteria**		**Weighted score for options**
		Method validity	Output suitability	Input data resolution	Input data integrity	Process clarity	Requirement for resources	
	Criteria rank =	2	1	4	3	5	6	
	Criteria weight =	0.241	0.297	0.139	0.188	0.091	0.045	
Local data gathering		75	100	100	83.1	25	100	84.1
Renewables Ninja		75	100	75.7	84.3	100	100	88.9
Synergistic combination: Renewables Ninja + Local data gathering		75	100	100	84.3	100	100	91

7.8. Chapter 7 conclusion

The aim of this chapter was to demonstrate the use of the LZCT assessment method selection framework through application to a case study of a CES on the Isle of Eigg in Scotland. This has been achieved through full application of the steps laid out in the definition of the framework in Chapter 5.

In Step 1 of the framework, the decision-makers and requirements of the decision-making process were identified. This was the Isle of Eigg Heritage Trust, a community body set up to manage community ownership of the island and which is made up of several community members. The requirements of the decision-making process were to select the most appropriate LZCT assessment methods to be used to assess possible future energy supply on Eigg so that these could be used in the modelling of a possible CES on Eigg. The motivation behind this was a secure energy supply for the community, and it was assumed that there was sufficient funding to employ experts to undertake any necessary analysis of the CES.

Next, in Step 2 of the framework, several exemplar wind turbine assessment methods were input into the framework tables. As several of these methods require multiple input sources (e.g. from climate data and turbine specifications), Step 3 saw the ranking, weighting and scoring of methods based on these input sources. This provided input to Step 4 which ranked, weighted and scored the “input data integrity” sub-criteria: “Data measurement period”, “data accuracy” and “data reliability”. This in turn provided input to Step 5, which ranked, weighted and scored the primary criteria of “Method validity”, “Output suitability”, “Input data resolution”, “Input data integrity”, “Process Clarity” and “Requirement for resources”. A final weighted score was then obtained through linear addition for each method.

The final step explored the possible combination of methods to create syntheses of methods. For wind turbine assessment methods the most beneficial combination was PHPP, HOMER and Local data gathering. For the LZCT assessment methods, a combination of Renewables Ninja and Local data gathering was found to be most beneficial. These syntheses of methods were recommended for the assessment of wind turbines for the case study.

This chapter has successfully demonstrated the use of the LZCT assessment method selection framework, which can effectively select the most appropriate LZCT assessment method for a given situation; based on a series of criteria and weights which change depending on case-by-case priorities. It would appear that due to inherent differences and weaknesses in methods, combinations of methods will often be the most appropriate solution for a case study.

8. Chapter 8 - An MCDM Framework for Selection of Modelling Tools. Use of COTSSSP to Develop a Framework to Select Modelling Tools for Community Energy Systems

8.1. Chapter 8 introduction

It has been established in Chapter 4 that COTSSSP [105] will be taken forward as the basis of an MCDM framework to select modelling tools for a CES. The COTSSSP plus SMARTER combination used in the Demand and LZCT Assessment Method selection frameworks is not appropriate in this case due to the high number of modelling tool functional characteristics that exceed the range of effective SMARTER application. These modelling tool functional characteristics will be characterised as “essential”, “desirable” or “not applicable” for the given situation, and modelling tools selected primarily based on their support for essential functionality, and secondarily based on support for “Desirable” features.

MCDM application should be guided by input from an expert team. As discussed in introduction to Chapter 2, the author has 4 years of accumulated knowledge working with CES analysis tools and methods. Within the scope of this research, the author’s experience was considered a suitable proxy for an expert team. In addition, the author worked as part of a decision-making team made up of energy experts from a university department with experience in CES development, with input from industry energy consultants.

This chapter will develop the COTSSSP-based framework, and aims to: (i) categorise and document capabilities of tools suitable for modelling CESs for the planning design stage with focus on incorporation of storage and DSM, and (ii) develop a selection process based on these documented capabilities to identify tools suitable for modelling in a specific situation. This will be achieved through:

- An initial screening process to identify potentially suitable modelling tools.
- Categorisation and tabulation of modelling tool capabilities and characteristics.
- Development of a COTSSSP- based modelling tool selection process using the tables.

The framework will then be demonstrated through application to a case study in Chapter 9.

The scope of the work presented here has been limited to modelling tools designed for hourly or sub hourly timestep modelling of community systems containing LZCTs, storage and DSM, for use at the planning stage. More detailed building and system design tools have been considered outside of the scope of this work.

There is an increasing trend towards using modelling tools in conjunction with other modelling tools or external software such as MATLAB [58], GEN-OPT [198], EnergyTRADE [199] etc. particularly to support mathematical optimisations or realistic controls. These multi-tool processes are also outside the main focus of this work, but will be covered in the discussion in Chapter 10.

The author recognises that modelling tools are continuously being developed and that the screening analysis and the tool classification exercise will need to be refreshed periodically via literature review approximately once a year. This work, in addition to providing a current snapshot, provides a useful framework for this refresh within the context of the proposed tool selection process.

8.2. Initial screening process to identify potentially suitable Modelling Tools

An initial list of 51 modelling tools with some ability to model an energy system was derived from: literature including review papers and papers describing the development and application of tools; tool user manuals and websites; and communications with tool providers. Tools captured in previous reviews but clearly not capable of modelling community scale energy systems were discounted, for example, Envi-met is a microclimate and landscaping tool [200], and Radiance is used in daylight prediction [201].

A set of criteria were applied to the 51 modelling tools in order to determine in more detail their potential suitability (Table 36). A tool passed the criteria if it could be used at community scale (i.e. was defined as such or had a case study demonstrating this capability), was appropriate to the planning stage, incorporated LZCTs, storage and DSM, had an hourly or sub-hourly timestep and could cover either thermal or electrical energy supply. The screening process is captured in Table 36 along with relevant references.

This process resulted in the identification of 15 tools suitable for modelling community scale energy systems incorporating LZCTs, storage and DSM, for use at planning design stages. Two of the 15, MODEST and Mesup/PlaNET were discounted due to lack of accessible information required for more detailed analysis. This left 13 tools to be carried forward into the categorisation of capabilities and tool selection process.

The following are explanations of the tool capabilities used to filter the tools at this stage:

Community scale: This criterion is met if the tool manual, guidance documentation or associated publications had specifically described the tool as applicable at community scale.

Community scale case study: Some tools identified as being primarily for ‘national’ or ‘regional’ planning rather than for community scale had available case studies or other documentation demonstrating application at community scale so were included; study references are given in the table.

Planning-level design: Tools capable of modelling for planning-level design were deemed to be in scope and to pass this criterion. More detailed building or system design tools, which require very detailed user inputs to describe each individual building and system component, were deemed not to meet the criteria. This is due to the high level of detail and corresponding resource requirement to use such tools to model several buildings within a community.

LZCT: Modelling of at least one LZCT was imposed as a minimum.

Storage and DSM functionality: Modelling of at least one form of storage and DSM was imposed as a minimum.

Time step: Criterion met if capable of a time step of one hour or less.

Electrical and/or thermal modelling: The criterion imposed was the ability to either model electrical or thermal networks. Community systems can consist of electrical, thermal and transport demands; electrical and thermal generating components; microgrid networks; transport fuel systems; thermal networks; and various DSM technologies interacting across the spectrum. Integration of these energy sectors can provide synergistic benefits, often resulting in a higher penetration of renewable supply [94], [202]. While an *ideal* energy system modelling tool would combine all these energy vectors, it was recognised that many community system design tasks utilise just one, so this was set as the minimum criteria.

Table 36: Initial Modelling Tool screening

Modelling Tools	Criteria met?	Community scale	Case study	Planning level design	LZCT	Storage/DSM	Time step	Electrical	Thermal	References used
AEOLIUS	No	National/regional	No	Yes	Yes	Yes	Minutes	Yes	No	[91]
Balmorel	No	No	No	Yes	Yes	Yes	Hourly	Yes	Yes	[203]
BCHP Screening Tool	No	No	No	Yes	No	Yes	Hourly	Yes	Yes	[91], [204]
Biomass Decision Support Tool	Yes	Yes	-	Yes	Yes	Yes	Hourly	No	Yes	[205]
CitySim	No	Yes	-	No	Yes	Yes	Hourly	Yes	Yes	[95], [206], [207]
COMPOSE	Yes	Yes	-	Yes	Yes	Yes	Hourly	Yes	Yes	[91], [94]
DECC 2050 Calculator	No	No	No	Yes	Yes	Yes	Yearly	Yes	Yes	[208]
DER-CAM	Yes	Yes	-	Yes	Yes	Yes	5 mins	Yes	Yes	[209], [210]
E4Cast	No	No	No	Yes	Yes	Yes	Yearly	Yes	Yes	[91]
EMPS	No	No	No	Yes	Yes	Yes	Weekly	Yes	No	[91], [211]

EnergyPlan	Yes	National/regional	Yes	Yes	Yes	Yes	Hourly	Yes	Yes	[81], [84]
EnergyPRO	Yes	Yes	-	Yes	Yes	Yes	Minutes	Yes	Yes	[77], [212]
ENPEP-BALANCE	No	National/regional	No	Yes	Yes	No	Yearly	Yes	Yes	[91], [94], [98]
ESP-r	No	Yes	-	No	Yes	Yes	Seconds	Yes	Yes	[56], [57]
ETEM/Markal-lite	No	Yes	-	Yes	Yes	Yes	Yearly	Yes	Yes	[98], [213], [214]
eTransport	Yes	Yes	-	Yes	Yes	Yes	Hourly	Yes	Yes	[215], [216]
GTMax	No	No	No	Yes	Yes	Yes	Hourly	Yes	Yes	[91], [217]
H2RES	Yes	Yes	-	Yes	Yes	Yes	Hourly	Yes	Yes	[84], [218], [219]
HOMER	Yes	Yes	-	Yes	Yes	Yes	Minutes	Yes	Yes	[3], [79], [220]
Hybrid2	Yes	Yes	-	Yes	Yes	Yes	Minutes	Yes	No	[221], [222]
HYDROGEMS	No	Yes	-	No	Yes	Yes	Minutes	Yes	No	[91], [223]
IDA-ICE	No	No	No	No	Yes	Yes	Minutes	No	Yes	[95]
iHOGA	Yes	Yes	-	Yes	Yes	Yes	Minutes	Yes	No	[224]–[226]
IKARUS	No	No	No	Yes	Yes	Yes	5 years	Yes	Yes	[91], [98]
INFORSE	No	No	No	Yes	Yes	Yes	Yearly	Yes	Yes	[91]
Invert	No	National/regional	Yes	Yes	Yes	No	Yearly	Yes	Yes	[91], [227]

KULeuven OpenIDEAS framework	No	Yes	-	No	Yes	Yes	Minutes	Yes	Yes	[91], [228], [229]
LEAP	No	No	No	Yes	Yes	Yes	Yearly	Yes	Yes	[98], [230], [231]
MARKAL/TIMES	Yes	Yes	-	Yes	Yes	Yes	Hourly	Yes	Yes	[232], [233]
MERIT	Yes	Yes	-	Yes	Yes	Yes	Minutes	Yes	Yes	[234]
Mesap/PlaNet	Yes	Yes	-	Yes	Yes	Yes	Minutes	Yes	Yes	[91], [98], [235]
MESSAGE	No	No	No	Yes	Yes	Yes	5 Years	Yes	Yes	[91], [98], [216], [236]
MiniCAM	No	National/regional	No	Yes	Yes	Yes	15 years	Yes	Yes	[91]
MODEST	Yes	Yes	Yes	Yes	Yes	Yes	Hourly	Yes	Yes	[91], [237], [238]
NEMS	No	No	No	Yes	No	Yes	Yearly	Yes	Yes	[91]
Neplan	No	Yes	-	No	Yes	Yes	Minutes	Yes	Yes	[239]
NetSim	No	Yes	-	No	Yes	No	Hourly	No	Yes	[240], [241]
ORCED	No	No	No	Yes	Yes	Yes	Hourly	Yes	No	[235], [242]
PERSEUS	No	No	No	Yes	Yes	Yes	36-	Yes	Yes	[91]

							72/year			
Polysun	No	No	No	Yes	Yes	Yes	15 minutes	Yes	Yes	[58], [243]
PRIMES	No	No	No	Yes	Yes	Yes	Yearly	Yes	Yes	[240], [244]
ProdRisk	No	Yes	-	Yes	Yes	Yes	Hourly	Yes	No	[91], [245]
RAMSES	No	No	No	Yes	Yes	Yes	Hourly	Yes	Yes	[15], [91]
RETScreen	No	Yes	-	Yes	Yes	Yes	Monthly	Yes	Yes	[91], [98], [202], [246]
SimREN	Yes	Yes	-	Yes	Yes	Yes	Minutes	Yes	Yes	[91], [230], [247]
STREAM	No	National/regional	No	Yes	Yes	Yes	Hourly	Yes	Yes	[248]
Termis	No	Yes	-	No	Yes	No	Minutes	No	Yes	[249], [250]
TRNSYS	No	Yes	-	No	Yes	Yes	Seconds	Yes	Yes	[89]–[91], [94], [95], [226]
UniSyD3.0	No	No	No	Yes	Yes	Yes	Bi-weekly	Yes	Yes	[91]
WASP	No	Yes	-	Yes	Yes	Yes	12/year	Yes	Yes	[91]
WILMAR Planning Tool	No	No	No	Yes	Yes	Yes	Hourly	Yes	Yes	[91]

Key: Dark shading = tool does not pass filter, light shading = tool may fail filter

8.3. Categorisation of Modelling Tool capabilities

For the 13 tools that passed the initial screening, capability tables were generated that document:

- Input data requirements and input support capabilities.
- Electrical and thermal supply technology modelling capabilities including district heating.
- Design optimisation, outputs capabilities, controls and DSM modelling capabilities.
- Storage modelling capabilities and underlying storage models.
- Practical considerations.

These tables are intended to be useful in the modelling tool selection process (described later in Section 8.4) by providing information on the capability of tools to be assessed against requirements for a specific CES analysis.

8.3.1. Input data requirements and input support capabilities

Modelling tools have different levels of input data requirements; some tools require the energy demand profiles, local climate, system characteristics, or generation profiles to be explicitly input as time series directly by the user. Other tools have embedded functions and libraries that provide support in generating detailed datasets from simple inputs, and/or support a mix of both directly entered and tool generated calculation inputs. This functionality could be “essential”, “desirable”, or “not applicable” depending on the case study and availability of data or expertise.

The key characteristics related to data input requirements for the various tools are captured in Table 37 and described below.

Table 37 - Input data support capabilities

Modelling tools	Demand profile generator	Resource assessor	Supply profile generator
Biomass Decision Support Tool	Yes	No	Modeller
COMPOSE	No	No	Database and input
DER-CAM	No	S, T, Wi	Modeller
EnergyPLAN	No	No	Database and input
EnergyPRO	Yes	B, H, S, T, Wi	Modeller
eTransport	Yes	Yes*	Modeller
H2RES	No	B, H, S, Wi	Modeller
HOMER	Yes	B, H, S, T, Wi	Modeller
Hybrid2	Yes	S, Wi	Modeller
iHOGA	Yes	H, S, Wi	Modeller
MARKAL/TIMES	No	B, H, S, T, Wi	Modeller
Merit	Yes	S, T, Wi	Modeller
SimREN	Yes	Yes*	Modeller

Resource Assessor Key: Biomass (B); Hydro (H); Solar radiation (S); Temperature (T); Wind (Wi)

***indicates that a resource assessor exists but the specifics were unable to be determined.**

8.3.1.1. Demand profile generator

Modelling tools were deemed to contain a demand profile generator ("Yes" in Table 37) if functionality exists to support synthesis of electrical, thermal or fuel demand profiles in hourly or sub-hourly time steps from simple inputs such as monthly or annual bill data or descriptions of building numbers and types, demographics, etc. Others which take the approach that either explicit half hourly or hourly metered data needs to be obtained, or potentially generated using a secondary modelling process (e.g. using building performance simulation tools), were categorised as "No" for this category.

8.3.1.2. Resource assessor

A resource assessor gives access to weather and other resources (e.g. solar radiation, wind, water, biogas and biomass) in a suitable data input format (e.g. from national or international datasets) based on simple inputs (e.g. location). The resources covered were identified for each tool.

8.3.1.3. Supply profile generator

A supply profile generator provides electrical, thermal or fuel-producing system outputs for use in the modelling. "Modeller" describes a tool which generates the supply profile from the resource input (e.g. climate) and the device specifications. For example, in HOMER, local wind speeds (the resource input) and a specific wind turbine specification (a power curve and other details) are used to calculate the wind turbine supply profile. "Database and input" describes a tool where the hourly or sub hourly supply profiles are input directly requiring the user to perform some outside tool calculations or source such datasets.

8.3.2. Electrical and thermal supply technology modelling capabilities

Modelling tools vary with respect to the range of supply technologies that can be directly modelled. Table 38**Error! Reference source not found.** captures information about available supply technologies within the different tools and more detailed description is given below.

Table 38 - Electrical and thermal supply technologies and district heating

Modelling tools	Electrical supply	Thermal supply	District heating
Biomass decision support tool	No	FBo	Yes
COMPOSE	B, C, CHP, G, Gr, PV, Wi	CHP, EBo, FBo, HP, ST	No
DER-CAM	CHP, D, G, Gr, PV, Wi	CHP, EBo, FBo, Geo, HP, ST	No
EnergyPLAN	B, C, CHP, D, G, Geo, Gr, GrS, H, N, PP, PV, T, Wa, Wi	CHP, EBo, FBo, Geo, HP, I, ST, Was	Yes
EnergyPRO	B, C, CHP, D, G, Gr, H, PV, Wi	CHP, EBo, FBo, HP, ST	Yes
eTransport	CHP, Gr, PP	CHP, FBo, HP	Yes
H2RES	B, C, D, G, GrS, H, PV, Wa, Wi,	EBo, FBo	No
HOMER	B, C, CHP, D, G, Gr, H, PV, Wi	CHP, FBo	No
Hybrid2	D, PV, Wi	None	No
iHOGA	D, G, Gr, H, PV, Wi	None	No
MARKAL/TIMES	B, C, CHP, D, G, Geo, Gr, GrS, H, N, PP, PV, T, Wa, Wi	CHP, EBo, FBo, Geo, HP, I, ST, Was	No
Merit	C, CHP, G, GrS, PV, Wi,	CHP, HP, ST	No
SimREN	Geo, H, PP PV, Wi	CHP	No

Key:

Electrical: Biomass power plant (B); Coal power plant (C); Combined heat and power plant (CHP); Diesel plant (D); Gas plant (G); Geothermal plant (Geo); Grid (Gr); Grid simple (GrS); Hydro (H); Nuclear (N); Generic power plant (PP), Photovoltaic (PV); Tidal (T); Wave (Wa); Wind (Wi)

Thermal: Combined heat and power (CHP); Electric boiler (EBo); Fuel boiler (FBo); Geothermal (Geo); Heat pump (HP); Industrial surplus (I); Solar thermal (ST); Waste incineration (Was)

A wide range of electrical supply systems can be modelled; most tools support modelling of connection to the external electricity grid. Two categories have been assigned for modelling of the grid connection: “Grid simple” allows for limitless import and export, with static pricing; more complex “Grid” models include features such as connection limits and charges, complex time based import and export tariffs etc.

District heating is becoming more popular in the UK [251], [252], and is ubiquitous in Scandinavia and Eastern and Central Europe [253]. It has potential to increase energy system overall efficiency and provide flexibility for more effective use of waste heat and renewables using thermal storage which is much cheaper at district scale than for individual buildings and much cheaper than an equivalent capacity of electrical storage [254]. It is therefore important to consider district heating while it will not necessarily be appropriate in all circumstances.

The modelling of district heating systems, if available in the tools, is only as an estimated heat loss. This is a continuous heat loss as a percentage of peak load in the Biomass Decision Support Tool, or a percentage of real-time load as in EnergyPRO. The heat demand density, distribution temperature and other factors such as controls which have a large effect on ancillary energy use and losses in district systems are not directly considered and are required to be captured by the user in inputting thermal demand profiles.

8.3.3. Design optimisation and output capabilities.

Two important attributes in supporting design tasks are the capability of the modelling tool to aid the identification of optimum design solutions, and the ability of the tool to directly provide outputs required to support decision making. Key capabilities of the 13 tools in these areas are captured in the first two columns of Table 39 and further discussed below.

Table 39 - Design optimisation, outputs, controls and DSM controls capabilities

Modelling tools	**Design optimisation**	**Outputs**	**Controls**	**DSM control**
Biomass Decision Support Tool	S	E, EP, FA, FC, RP, SA	FO, NO	FO
COMPOSE	E, F	E, EP, FA, FC, SA	MO, OO (F)	OO (F)
DER-CAM	E, F	A, E, EP, FA, FC, SA	DC, EV, LS, MO, OO (F, E)	DC, EV, LS, OO (F, E)
EnergyPLAN	No	E, EP, FA, FC, SA, RP	FO, LS, MO, OO (F)	FO, LS, OO (F)
EnergyPRO	No	E, EMI, EP, FA, FC, SA	EV, MO, NO, OO (F), UO	EV, OO (F)
eTransport	F	E, EMI, EP, FA, FC, SA	MO, OO (F)	OO (F)
H2RES	No	EP, FC, RP, SA	FO, MO	FO
HOMER	F	A, E, EP, FA, FC, RP, SA,	AC, LS, MO, NO, OO (F), UO	LS, OO (F)
Hybrid2	No	EP, FA, SA	FO, LS, MO, NO	FO, LS
iHOGA	Single: F Double or triple: combination of A, E, F,	A, E, EP, FA, FC, HDI, JC, RP, SA	FO, MO, NO, OO (F)	FO, OO (F)

	HDI, JC, NPC			
MARKAL/TIMES	F	E, EMI, EP, FA, FC, RP, SA,	MO, NO, OO (F)	OO (F)
Merit	No	EP, FC, M, SA	FO, LS, MO	FO, LS
SimREN	No	EMI, EP, SA	-	-

Key:

Design Optimisation: Autonomy (A); Emissions (E); Financial (F); Human development index (HDI); Job creation (JC); System (S)

Outputs: Autonomy (A); Emissions (E); Energy market interaction (EMI); Energy production (EP); Financial analysis (FA); Fuel consumption (FC); Human development index (HDI); Job creation (JC); Demands/supply match (M); Renewable penetration (RP); System analysis (SA)

Controls/DSM Controls: Advanced control (AC); Demand curtailment (DC); Electric vehicles (EV); Fixed order (FO); Load shifting (LS); Modulating output (MO); Non-modulating output (NO); Operational optimisation (OO) with objective function in brackets; User-defined order (UO)

8.3.3.1. Design optimisation

Optimisation modelling tools find the minima, or maxima, for a defined objective function by systematically searching a defined modelling space according to a mathematical algorithm. Design optimisation involves a search for the optimal system with respect to combination and sizing of components. Most of the reviewed tools where they support optimisation use a full factorial deterministic approach based on user defined inputs to solve the optimisation problem and use a simple financial and/or carbon emissions objective. HOMER historically has executed a grid search based on user defined inputs specifying the system options to be included but recently provided an update allowing users to only input upper and lower limits to the grid search. iHOGA was the only identified tool with multi-objective function capability; it includes a choice of available objective functions and embedded genetic algorithms [255]. The Biomass Decision Support Tool supports the optimisation of thermal storage size. A number of reviews have covered the mathematical optimisation methods that could potentially be employed [256], [257]. Tools which do not directly support mathematical optimisation could be used within an external mathematical optimisation process by an iterative approach, but this can be logistically complex or require advanced software skills to automate.

8.3.3.2. Outputs

The outputs are key in assessing system performance. Different modelling tools focus on different aspects of the system performance; most tools provide financial analysis such as cost/kWh of energy produced or information on energy market interactions; some are purely technical and focus on the energy production, system analysis, demand/supply match, or fuel consumption; others assess emission and renewable penetration, and others consider social factors such as job creation and the human development index. Specific tool outputs can be used in external calculations to generate a wider range of analysis outputs but only the in-tool capabilities are documented here.

8.3.4. Control modelling capabilities including DSM

The ability to correctly capture controls is important in assessing the performance of community scale energy systems and particularly so when assessing the impacts of storage and DSM in such systems. Modelling tools often have in-built control logic intended to mimic real or idealised controls, it is important to comprehend and assess the control regime underpinning each of the models. Key capabilities of the 13 tools are captured in Table 39 and further discussed below.

8.3.4.1. General control capabilities

Controls regulate how supply, storage and DSM technologies meet loads by determining the control logic and constraints applied. A simple community scale system control strategy can include: (i) an order of dispatch for the different resources, and (ii) a set of constraints.

8.3.4.1.1. *Operational optimisation*

Operational Optimisation (OO) control is where the modelling tool optimises, at each time step, the order of dispatch of supply, storage, and DSM technologies to satisfy an objective function which may relate to cost, emissions, etc. There are differences in detailed logical implementation between tools; a general description is given here.

Most tools use the OO control chronologically i.e. calculations are performed at each individual time step to establish an optimum based on prevailing conditions at that time step only, before the next time step is then considered. Storage is generally charged and discharged when it is deemed favourable to do so according to the specific logical implementation and objective function. Typically charging will occur when there is excess energy from renewable or non-modulating supply where storage is deemed to have benefit over export or curtailment, or where grid parameters, e.g. tariff, make charging from grid advantageous. Discharge from available storage is generally treated as a dispatchable supply option. The value attached to storage charge and discharge takes account of characteristics of the storage system, e.g. efficiencies and costs, plus parameters such as tariffs and carbon contents. For example, in HOMER the discharge energy cost includes average charge energy cost, efficiencies, and battery wear, lifetime and replacement costs.

OO control is applied non-chronologically in some tools e.g. in EnergyPRO the whole calculation period is scanned for energy supply costs and an optimised supply schedule determined, with excess low cost generation charging storage and discharge occurring to meet demand in subsequent favourable high cost time steps. These OO control functionalities may replicate real control systems for situations where local renewable consumption is prioritised or where a set tariff structure is established for energy import and export; the non-chronological OO implementation may in some circumstances provide a somewhat optimistic view of system performance as perfect foresight is implied.

8.3.4.1.2. *Fixed order*

Fixed Order (FO) control is where there is an available set of functions with pre-defined order of dispatch of supply, and fixed conditions for the use of storage and DSM technologies. Dispatchable supply is dispatched in a fixed order in periods where non-dispatchable, typically renewable, supply is below demand. EnergyPLAN, H2RES, and Merit charge electrical storage in periods of excess renewable production and prioritise discharge from electrical storage over generators and power plants. In Merit thermal storage discharge is prioritised over other thermal supply options. In EnergyPLAN thermal storage charging is prioritised to absorb excess electricity or heat production and discharged to avoid non-renewable generation. In iHOGA batteries can charge/discharge at fixed, user input tariff values. In the Biomass decision support tool excess heat from the biomass boiler is stored in a thermal storage and discharged when demand exceeds supply. EnergyPLAN includes several selectable functions for dealing with excess electricity production. Hybrid2 contains embedded functionality for 13 pre-defined fixed order controls relating to the practical performance of electric systems [221]

8.3.4.1.3. User-defined order

User-defined Order (UO) control is where the order of dispatch, for at least some part of the supply, is defined by the user. For example, UO in EnergyPRO requires all supply options to be given an order of preference, which can also include separate priorities for production to satisfy different (peak, high, low) loads; storage priority setting is not an option and in this tool storage operation always follows the OO control strategy.

8.3.4.1.4. Modulating output

Modulating output (MO) control applied to a dispatchable supply allows modulation of output to match load above some minimum supply output level. In all modelling tools the grid connection, if enabled, can modulate output to follow electrical load with a minimum supply level of zero. HOMER can only designate grid or generator supplies to this control while in EnergyPRO, DER-CAM, and eTransport any dispatchable supply can be assigned.

8.3.4.1.5. Non-modulating output

Non-modulating output (NO) control sets the constraint that a designated supply must run at a fixed output whenever it is running. In the Biomass Decision Support Tool, the designated supply is the biomass boiler. In EnergyPRO the user selects supplies. In iHOGA and HOMER the designated supplies are the generators. In these two tools a set state of charge can be specified and the designated supply will continue operating, regardless of availability of renewable generation, until the set point is reached. This mimics a common feature in real systems used to maximise battery life but which reduces the potential for renewable inputs to the store.

8.3.4.1.6. Advanced control

HOMER offers the capability to use Advanced Control (AC) strategies where users can define more complex control operating regimes than those previously outlined by interfacing with externally written code in MATLAB [258].

8.3.4.2. DSM related control capabilities

The general control modelling capabilities described in the previous section, such as OO and FO, can be used where there is storage in the system to capture DSM functionality associated with storage charging and discharging. Several tools have further DSM specific functionality to represent ‘Load Shifting’, ‘Demand Curtailment’ and ‘Electrical Vehicles’ in the system. All DSM related control capabilities are captured in the 'DSM control' column of Table 39, the further DSM specific functionalities are described below.

8.3.4.2.1. Load shifting

Load shifting (LS) is where a flexible load is defined which can be met or deferred to a later time step within a limited deferrable time period, while incurring no loss. The flexible load can be input as a specific energy quantity over the deferrable period in EnergyPLAN which uses 1 day, 1 week, or 4 weeks deferrable periods, and in Hybrid2 which allows users to input the deferrable period. In DER-CAM the flexible load is sized as a percentage of the main load over a 1 day deferrable period. The flexible loads in these tools are actuated when lowest cost or surplus energy is available within the flexibility period. HOMER and Hybrid2 can accommodate more detailed model parameters such as: average deferrable load (kWh/day), capacity (kWh), peak load (kW), and minimum load ratio, flexible load in these tools is treated as secondary to the main load but prioritised over charging storage.

8.3.4.2.2. Demand curtailment

Demand curtailment (DC) is where demand can be curtailed under certain conditions and unlike load shifting, is not shifted but reduced. DER-CAM is the only reviewed modelling tool capable of modelling DC and curtails demand when tariff prices exceed a user defined curtailment cost (£/kWh) within an annual maximum number of curtailment hours. There is also additional functionality to allow for up to 5 daily hourly profiles capturing the proportions of the main load which can be curtailed at each time step.

8.3.4.2.3. Electric vehicles

Electric vehicles are going to play a vital role in the future of energy systems [259], [260], and there has been research into the system flexibility they can provide [261], [262]. Only two of the identified modelling tools include models for an electric vehicle to grid interaction. EnergyPRO has a model based on the energetic capacity of the batteries in the cars, and limits on the charging and discharging along with associated efficiencies. The demand for the vehicles is input as a time series and there are options accounting for availability. Charging/discharging can be set to on/off with charging allowed at zero demand, it can be set to proportional to the driving demand time series, or it can be set its own time series. EnergyPLAN contains a similar model. The inputs are for maximum discharge/charge, capacity of batteries in vehicles, efficiencies, and a time series for demand. Simpler assumptions are made on the availability, with the fraction of cars driving at peak demand and of cars parked used to calculate the connection of cars to grid.

8.3.5. Storage modelling capabilities and underlying models

This section looks at relevant capabilities of the 13 screened modelling tools and underlying models with respect to storage functionality. Such functionality enables DSM and, in the reviewed tools, is used with the operational optimisation and fixed order controls (see Section 8.3.4).

Storage capabilities are captured in two look up tables for use in tool selection. Table 40 describes the range of storage modelling capabilities available in each tool, with more detailed descriptions of these capabilities in the sub-sections below. Table 41 gives a summary of the more advanced models i.e. more detailed models than the simple storage model (SSM) for each storage technology; SSM can be used to model all storage types and is not included in Table 41 for this reason. A brief summary of each capability and underlying model is given below, further details including model equations can be found in the relevant references.

Table 40 - Storage modelling capabilities and underlying models

Modelling Tools	Electrical storage	Thermal storage	Fuel synthesis	Fuel storage
Biomass Decision Support Tool	No	MB	No	B
COMPOSE	KiBaM	CS, SSM	No	No
DER-CAM	FB, SSM	MB	No	No
EnergyPLAN	CAES, PH, SSM	SSM, STS	BF, BG, EF, GtL, H	G, O, M
EnergyPRO	PH, SSM	CS, MB	BF, BG, EF, GtL, H	G, O, M
eTransport	Yes	Yes	Yes	Yes
H2RES	Yes	Yes	No	Yes
HOMER	FB, KiBAM, MkiBaM, PH, SSM	No	H	H
Hybrid2	EKiBaM	No	No	No
iHOGA	KiBAM, MKiBaM, SSM	No	H	H
MARKAL/TIMES	Yes	Yes	Yes	Yes
Merit	EKiBaM	SSM	No	No
SimREN	Yes	No	No	No

Key:

Electrical: Compressed air energy storage model (CAES); Extended kinetic battery model (EKiBaM); Flow battery model (FB); Kinetic battery model (KiBaM); Modified kinetic battery model (MKiBaM); Pumped hydro model (PH); Simple storage model (SSM)

Thermal: Cold storage model (CS); Moving boundary model (MB); Seasonal thermal storage model (STS); Simple storage model (SSM)

Fuel synthesis: Biofuel (BF); Biogas (BG); Electrofuel (EF); Gas to liquid (GtL); Hydrogen (H)

Fuel storage: Biomass (B); Gas (G); Hydrogen (H); Methanol (M); Oil (O)

*"Yes" indicates that the tool has a certain capability but specific models used were not able to be confirmed; these tools were assumed to have SSM as minimum electrical and thermal storage models

Table 41 - Electrical and thermal storage technologies and advanced models (beyond SSM)

Electrical storage (ES) type	Advanced ES models used	Thermal storage (TS) type	Advanced TS models used
Lead-acid battery	EKiBaM, KiBaM, MKiBaM	Hot water tank	MB
Li-ion battery	EKiBaM, KiBaM, MKiBaM	Cold storage	CS
Flow battery	FB	Seasonal thermal storage	STS
Pumped hydro	PH	N/A	N/A
CAES	CAES	N/A	N/A

Key:

Electrical: Compressed air energy storage model (CAES); Extended kinetic battery model (EKiBaM); Flow battery model (FB); Kinetic battery model (KiBaM); Modified kinetic battery model (MKiBaM); Pumped hydro model (PH); Simple storage model (SSM)

Thermal: Cold storage model (CS); Moving boundary model (MB); Seasonal thermal storage model (STS); Simple storage model (SSM)

Note: SSM can be used to model all storage types and is not included

8.3.5.1. Electrical storage modelling capabilities and underlying models

Electrical storage is a general term used here to include electrochemical (li-ion, flow, lead-acid batteries), electromagnetic (supercapacitors), and mechanical (CAES, hydro, flywheels) forms. Electrical storage can be represented using a number of different mathematical models, the different models used in the tools are categorised and described below. The level of detail required at the planning stage depends on the specifics of the system being modelled and the outputs to be derived from the modelling.

8.3.5.1.1. Simple storage model

A modelling tool possessing a Simple Storage Model (SSM), which can interact with supply and load, can model any storage technology. EnergyPLAN and EnergyPRO use the SSM to define all types of storage, including all electrical storage types. iHOGA, DER-CAM and HOMER support the use of the SSM, e.g. for high-performance batteries [15]. HOMER also recommends its use for simple pumped hydro storage systems. The SSM consists of a simple energy in/out balance via an energy store. Energy can enter the store below a threshold maximum charging rate up to a maximum store capacity. There can be self-discharge from the store e.g. a percentage or other function at each time step. Energy can leave the store below a threshold maximum discharging rate. For charging and discharging there are associated efficiencies, which combine with self-discharge to give a round-trip efficiency. Charge and discharge efficiencies are both generally fixed values. The SSM has fixed maximum charge and discharge rates independent of the state of the system, this approximation may be sufficient for some analyses, but may not be realistic in other cases, more detailed models are available. Storage lifecycle analysis is included in some tools with the SSM, e.g. in HOMER lifetime is modelled as both an energy throughput and time, however performance degradation effects are only included in the MKiBaM model described later.

8.3.5.1.2. Kinetic battery model

The Kinetic Battery Model (KiBaM) was first developed for modelling lead-acid batteries in hybrid energy systems [263]. It is described as a two tank model [50], where one tank holds the available energy to directly support charge and discharge and the other holds the bound energy which transfers energy to and from the available tank according to a defined exchange function representing the chemical process. The model supports charge/discharge rates as functions of stored energy in the two tanks. The underpinning electronic mechanisms are still somewhat simplified with voltage modelled only as a linear function of energetic state etc. iHOGA and HOMER both possess this model and have libraries of electrochemical batteries with parameters established from test data.

8.3.5.1.3. Extended kinetic battery model

Work was done to improve the KiBaM in terms of modelling voltage behaviour [264]. These models are denoted here as Extended Kinetic Battery Models (EKiBaM). Hybrid2 includes such an improved model [265], with voltage, charging and discharging efficiencies and current as non-linear functions of the state of charge. Merit also contains a different but similar model with improved voltage modelling [234].

8.3.5.1.4. Modified kinetic battery Model

A further Modified Kinetic Battery Model (MKiBaM) is used by HOMER and iHOGA to give deeper insights. This includes a thermal model component whereby the resistive properties of the battery produce heat which affects temperature, capacity and lifetime. Secondly, it involves cycle-by cycle degradation of the battery as a function of depth of discharge; this is accounted for using the Rainflow counting algorithm [266], which iHOGA also further utilises to account for corrosion effects over time. iHOGA offers customised models for lead-acid batteries [267], [268] and Li-ion batteries [269]–[271].

8.3.5.1.5. Flow battery model

Flow batteries can also be modelled explicitly with models which account for the independence between capacity and charge/discharge and other flow cell characteristics. Flow battery specific models based on manufacturers data are included in DER-CAM [272] and HOMER [50].

8.3.5.1.6. *Pumped hydro model*

Pumped hydro is often modelled using the SSM by factoring in the capacity and efficiency of the pump and generator as well as the capacity of the reservoir. EnergyPLAN and HOMER include pumped hydro as a technology using the SSM. Only EnergyPRO includes an explicit pumped hydro model and includes inputs such as reservoir volume, friction factors and head difference.

8.3.5.1.7. *Compressed air energy storage model*

A simple compressed air energy specific storage model (CAES) is included in EnergyPLAN, with a focus on the economic trading possible [273].

8.3.5.2. Thermal storage modelling capabilities and underlying models

Thermal storage allows for sensible or latent heat to be kept for meeting a demand later. It can include hot water tanks, brick radiator stores, phase change storage materials, and cold storages. It can also be designed for buildings or community scales. A summary of different thermal storage models including underlying equations is given by [93]. The tools that are the focus of this paper use only the least complex models; some of the limitations associated with this are discussed later. The categorisation of thermal storage models found in the tools is captured in Tables 40 and 41 and described below.

8.3.5.2.1. *Simple storage model*

The SSM model does not consider temperatures but only accounts for energy, and was described earlier for electrical storage in Section 8.3.5.1.1. EnergyPLAN uses the SSM to model all thermal storage technologies.

8.3.5.2.2. *Moving boundary model*

The most common model for thermal storage in the examined modelling tools is the moving boundary model (MB), where the additional inputs over the SSM are top and bottom tank temperatures. It assumes that there is no mixing between the upper hot zone and the lower cold zone and the thermocline boundary layer is infinitesimally small. This is again an energy balance model with inflows and outflows of energy moving the boundary layer up and down the store and stored energy calculated based on the thermocline position. The model does not explicitly capture temperature variation due to losses and destratification. This model is incorporated in the Biomass Decision Support Tool, DER-CAM, EnergyPRO, and Merit. The model can be adjusted in EnergyPRO using a utilisation factor which reduces the useful energy which can be used for supply. DER-CAM allows for different high temperature and low temperature stores within the system to allow for different heat generation devices [274]. EnergyPRO also uses the MB model for cold storage (CS) and was the only tool identified to have electrical, heat, and cold storage modelling capability.

8.3.5.2.3. Seasonal thermal storage model

A seasonal thermal storage model is included in EnergyPLAN. It is simplified and only two inputs are required: capacity, and ‘days of optimising storage’ which allows for the model to identify inter-seasonal variations in demand. [95] set out the state of art in modelling seasonal thermal storage in building-scale simulation tools, but in general this functionality is not supported in the tools analysed here apart from EnergyPLAN.

8.3.5.2.4. Other thermal storage models

Temperature variations, and therefore entropy considerations, are vital in real thermal storage analysis [275]. There may appear to be enough energy in a tank to meet the energy demand, but if the temperature does not meet the supply requirement it is not useful energy. The MB model does not account for changes in the temperature zones; there are no entropic considerations. The [93] summary of modelling approaches for sensible thermal storage tanks includes the MB model and highlights the models which would be used to include entropy, with increasing detail at the expense of computational and data input complexities.

8.3.5.3. Modelling of fuel synthesis and storage

Fuel synthesis is the production of fuels within a system creating a new energy vector which can be used across a range of energy sectors, and acts as storage to be used later [276]. EnergyPLAN, iHOGA and HOMER can model the synthesis of hydrogen. This is produced using electricity with an electrolyser to form hydrogen, stored in a hydrogen tank, and then converted to meet transport, heat, or electricity demands. All three technical components can be modelled within the three tools. EnergyPRO contains a simple model for the synthesis of any fuel. EnergyPLAN allows for synthesis of different types of fuel: biofuel, biogas, hydrogen from electrolysis, electrofuel, and gasification to liquid transport fuel. These fuels are used to form interactions between energy sectors, and ensure high-value energy is used for high-value processes.

These fuels must then be kept in storage. The Biomass Decision Support Tool can size biomass fuel storage, while iHOGA and HOMER can model hydrogen storage tanks. EnergyPLAN can model gas, oil and methanol storages, and EnergyPRO can model any fuel storage as a generic model.

8.3.6. Practical considerations

This table sets out practical considerations associated with selecting a modelling tool: cost, access, support, whether it is academic or commercial, user-friendliness, and whether there is existing available expertise.

Cost may be a vital factor in choosing a modelling tool and depends on the resources available to a user. A student is likely to choose a free tool which there is abundance of: Biomass Decision Support Tool, COMPOSE, DER-CAM, EnergyPLAN, iHOGA, Hybrid2, Merit and MODEST. Often tools are available at discounted prices for students. A government agency or an engineering consultancy may have the resources available to afford the cost for a tool such as 3,000+ EUR for EnergyPRO, 500-1500 USD for HOMER, or 1275-3130 EUR to manipulate the code for MARKAL/TIMES.

Accessibility is defined in terms of availability, purchase requirement, and if the tool was downloadable or browser-based. Available support as indicated by tool websites and verified by the authors is listed, and includes: user manual, available contact details, videos, training, and an online forum. The tools are classed as academic or commercial based on the development and ownership of the tools through either a university/research group, or a private company, respectively.

User friendliness was judged on the provision of an intuitive model-building pathway which was subjectively graded by the author at a low, medium, or high level according to the grading system laid out in [94]. This required first-hand knowledge of the tools so where the tool was not available to the author, the grade by [94] was referenced.

Most modelling tools require a significant investment in time to develop expertise in order to be used correctly and proficiently so there will be a strong practical driver to use a modelling tool which has established available expertise if this exists. If there is no established expertise available and the aim is to develop such an expertise then this driver will be less strong or zero.

Table 42 - Practical considerations for selection of Modelling Tools

Modelling Tools	**Cost**	**Access**	**Support**	**Academic / Commercial**	**User friendly**	**Available Expertise**
Biomass Decision Support Tool	Free	Download	User manual, videos, online course	Commercial	High	Yes/No[2]
COMPOSE	Free	Download	Videos, forum	Academic	Med	Yes/No[2]
DER-CAM	Free	Browser	User manual, videos, forum	Academic	Med	Yes/No[2]

EnergyPLAN	Free	Download	User manual, contact, videos, training, online course	Academic	High	Yes/No[2]
EnergyPRO	3,000+ EUR for all modules	Purchase	User manual, contact, training	Commercial	High	Yes/No[2]
eTransport	Not available	Not available	Not available	Academic	High[1]	Yes/No[2]
H2RES	Not available	Not available	Not available	Academic	Not available	Yes/No[2]
HOMER	Free 2-week trial, 500 - 1500 USD	Purchase	User manual, contact, videos, forum	Commercial/ Academic	High	Yes/No[2]
Hybrid2	Free	Download	User manual, contact	Academic	Not available	Yes/No[2]
iHOGA	Educational Free, 500 EU for 1 year	Purchase	User manual, forum, contact	Academic	Med	Yes/No[2]
MARKAL/TIMES	Costs 1275-3130 EUR	Download	User manual,	Academic	Low[1]	

	to manipulate source code		paid support, forum			Yes/No[2]
Merit	Free	Download	Training	Academic	Med	Yes/No[2]
SimREN	Not available	Not available	Not available	Commercial	Not available	Yes/No[2]

[1]From [94], [2] User to self-assess

8.4. COTSSSP MCDM Modelling Tool selection framework

The following outlines the stepwise, MCM modelling tool selection framework which was developed to aid in the selection of an appropriate tool(s) for a particular analysis for planning-level design of a CES incorporating storage and DSM, based on the COTSSSP MCDM technique developed by Sandia National Laboratories [105].

8.4.1. Determination of requirements

The first process step is to establish which of the modelling tool capabilities (documented in Tables 37-42) are "essential", "desirable" or "not applicable" and to assign values of 2, 1, and 0 respectively to each of these tool capabilities. This process requires that each of the capabilities described in the column headings and associated keys of the tables are individually considered against the requirements for the intended analysis. For example if we look at Table 37 then the three tool capabilities captured are "demand profile generator", "resource assessor", and "supply profile generator"; if the user requires the tool to provide demand profiles, weather data and renewable generation supply profiles from simple input data such as location and demographics then these capabilities would be considered "essential" and each of these capabilities would be assigned a value of 2; alternatively if the user has available data for demand, weather and renewable generation and supply (e.g. from monitored data) then these capabilities are "not applicable" so would be assigned a value of 0 and can be eliminated from further consideration; if the user can potentially source information and generate the demand, weather and renewable generation input data but this would be significant effort then this capability could be “desirable” and allocated a value of 1. Similarly, if we consider Table 38 it may be that it is “essential” that there is capability to model electrical generation with both PV and wind so each of these capabilities would be allocated a 2 while if there is no potential for hydro then this capability would be deemed “not applicable” and allocated a 0. When this process is complete, the “essential” and “desirable” capability requirements have been established, and then tools can be scored against them.

8.4.2. Scoring of Modelling Tools against requirements

Once the requirements have been established then each of the modelling tools can be scored against them. The first consideration is whether all the essential capabilities are available. If a given modelling tool has all the essential capabilities it can be considered further; those which do not pass this check can be discounted. For the tools which pass, their scores for the essential plus desirable capabilities are summed into an overall score and ranked with the most suitable tools having the highest scores. This process is described in more detail Chapter 9 through application to a case study.

8.5. Chapter 8 conclusion

The aim of this chapter was to develop a framework for the selection of modelling tools for a CES by (i) categorising and documenting of capabilities of tools suitable for modelling CESs for the planning design stage with focus on incorporation of storage and DSM, and (ii) developing a framework to select suitable tools based on these documented capabilities.

This has been achieved through (i) an initial screening process to identify potentially suitable tools, (ii) categorisation, tabulation and documentation of tool capabilities through analysis of all potentially suitable tools, and (iii) development of a tool selection framework based on the COTSSSP MCDM technique. This developed framework provides an intuitive, step-wise process for the decision-maker to select a range of suitable tools for further investigation for use in CES analysis for a given case study; a short demonstration of how to use the framework is show for a case study in Chapter 9.

9. Chapter 9 - Demonstration of COTSSSP MCDM Modelling Tool Selection Framework through Application to a Case Study

9.1. Chapter 9 introduction

This chapter sets out to demonstrate the use of the COTSSSP MCDM framework for modelling tool selection as described in Chapter 8. This shall be achieved through the application of the framework to the case study of the ecovillage of Findhorn.

Findhorn is an ecovillage in the north-east of Scotland with an ambition to transition to a local, low-carbon energy system. It consists of around 75 buildings, with a private wire electrical network, wind and solar generation, a grid connection, micro-district heating from biomass, and individual household heat pumps and solar thermal systems. The community could be said to be net zero carbon but has large electricity surpluses and shortfalls due to stochastic demands and renewable production. The community have an interest in the use of thermal and electrical storage with advanced controls as a potential route to achieving their aims. The community had previously been monitored as a research and demonstration site for advanced DSM [277].

9.2. Identification of decision-making requirements

The community overall objective is to increase their energy autonomy and use of local renewable energy resources; they have some concerns over the sustainability of biomass. To help achieve their objective they enlisted support from a university and after an initial scoping process identified 2 initial future illustrative scenarios to be investigated: 1) increased electrical generation plus battery storage, and 2) increased electrical generation plus heat pumps and large hot water tanks replacing the micro-district biomass heat source. The modelling tool selection process was then applied in order to identify suitable software to use for the investigation.

9.3. Application of MCDM Modelling Tool selection framework

The first step was to review the modelling tool capability requirements: demand profile generator, resource assessor, and supply profile modeller capabilities (Table 37) were all deemed to have zero value (i.e. not applicable) since multi-year sub-hourly data was readily available from monitoring.

Electrical supply technologies - wind, grid, and solar PV - were deemed to be essential (Table 38). Thermal supply modelling of fuel boiler (biomass fuel in this case) and heat pumps were deemed essential. Capability to model solar thermal and district heating in detail were scored desirable but not essential at this stage as the primary focus was on the electrical supply system and the available monitoring data included heat delivery from existing heat production units net of solar inputs and distribution losses.

Design optimisation capability (Table 39) was deemed desirable but not essential as the view was taken that the relatively simple range of options to be investigated could be covered through a full factorial deterministic investigation and modelling outputs analysed outside of the tool to establish potential optima. The output of hourly data allowing either: autonomy, emissions, or renewable penetration to be established was deemed essential; this level of system performance parameter output would then allow the other required outputs to be calculated outside of the tool.

For control capabilities (Table 39), either FO or OO control was deemed essential to support the required ordering of dispatch of supply and storage, in addition to the MO control inherent in all the tools for representing the grid. DSM specific control functionality was not required in this example.

Storage modelling capability was deemed essential for both electrical and thermal storage (Tables 40 and 41). It was deemed that the simple storage model was sufficient but that it would be desirable for more complex models to be available. Fuel synthesis and fuel storage are not required in this simple illustrative study.

These technical requirements are captured (in the top 4 rows of Table 43) and then each of the tools assessed against these requirements, where a tool has an essential or desirable capability then it scores 2 or 1 respectively against that capability, otherwise it scores 0. Once all the potentially capable tools have been assessed they are ranked: (i) first the tools which do not have all the essential are deemed to “fail”’ to meet the essential requirements and discounted and only those that “pass” this test considered further, (ii) the remaining tools are then ranked based on their cumulative score. This process is illustrated in Table 43, with the result in this case that 6 tools are capable with similar scores of either 20 or 21. These tools should then be further investigated

This example has been kept relatively simple for reasons of clarity and brevity; more complex situations would follow the same process.

Table 43 - Output from application of modelling tool selection process

	Essential Capabilities	Overall Score	Design optimisation	Outputs	Controls and DSM	Supply technologies							Storage			
	All essential capabilities met	**Score (essential + desirable)**	**Yes**	**Autonomy, emission, or RES**	**FO or OO**	**WT**	**PV**	**Fuel boiler**	**Grid**	**District Heating**	**Solar Thermal**	**Heat Pumps**	**Electrical Battery SSM**	**Electrical Battery >SSM**	**Hot water tank SSM**	**Hot water tank >SSM**
D=Desirable, E=Essential			**D**	**E**	**E**	**E**	**E**	**E**	**E**	**D**	**D**	**E**	**E**	**D**	**E**	**D**
Value			**1**	**2**	**2**	**2**	**2**	**2**	**2**	**1**	**1**	**2**	**2**	**1**	**2**	**1**
COMPOSE	Pass	21	1	2	2	2	2	2	2	0	1	2	2	1	2	0
DER-CAM	Pass	21	1	2	2	2	2	2	2	0	1	2	2	0	2	1
EnergyPRO	Pass	21	0	2	2	2	2	2	2	1	1	2	2	0	2	1
EnergyPLAN	Pass	20	0	2	2	2	2	2	2	1	1	2	2	0	2	0
MERIT	Pass	20	0	2	2	2	2	2	2	0	1	2	2	1	2	0
MARKAL/TIMES	Pass	20	1	2	2	2	2	2	2	0	1	2	2	0	2	0
eTransport	F	16	1	2	2	0	0	2	2	1	0	2	2	0	2	0

H2RES	F	16	0	2	2	2	2	2	2	0	0	0	2	0	2	0
HOMER	F	16	1	2	2	2	2	2	2	0	0	0	2	1	0	0
iHOGA	F	14	1	2	2	2	2	0	2	0	0	0	2	1	0	0
Biomass Decision Support Tool	F	11	1	2	2	0	0	2	0	1	0	0	0	0	2	1
Hybrid2	F	9	0	0	2	2	2	0	0	0	0	0	2	1	0	0
SimREN	F	6	0	0	0	2	2	0	0	0	0	0	2	0	0	0

9.4. Chapter 9 conclusion

The aim of this chapter was to demonstrate the application of the MCDM modelling tool selection framework. This has been achieved through application of the framework to the case study of the ecovillage of Findhorn. Tool capabilities were classed as “essential”, “desirable” or “not relevant” according to the decision-making requirements of the case study, which were to increase energy autonomy and use of renewable resources.

Tools scored 2 points for the inclusion of each “essential” capability, and an additional 1 for the inclusion of each “desirable” capability; tools without any “essential” capability were discounted.

This meant that only tools capable of modelling the “essential” requirements of current electrical supply technologies (wind, grid and solar PV), current heat supply technologies (biomass boiler and heat pumps), outputs (autonomy, emissions or renewable energy supply), controls (fixed order or operational optimisation), and basic electrical and thermal storage, would “pass” and be potentially suitable for use in modelling the case study.

Because of the scoring system, there was little differentiation between tools, with all potentially suitable tools receiving either 20 or 21 as overall score. The method therefore delivers a subset of potentially suitable tools rather than an “ideal” tool.

10. Chapter 10 - Discussion

Future community energy systems will contain supply technologies reliant on renewable sources which necessitate the inclusion of storage and DSM. These need to be carefully designed to ensure they are resilient, low-cost, and maximise use of renewable sources. Modelling is vital in achieving these aims; to perform this effectively, accurate and high-resolution energy demand and supply information is required as input to modelling tools. There are, however, several methods available for the generation of these supply and demand profiles, and several tools available for CES analysis, with no formalised frameworks to select the most appropriate combination for the analysis of a CES.

The aims of this piece of research were to address this by developing pre-modelling frameworks to support (i) demand assessment method selection, (ii) LZCT assessment method selection, and (iii) CES modelling tool selection.

This chapter describes the work undertaken to achieve these aims, discusses each framework and finishes by discussing the limitations of the research and potential for future work.

10.1. Achievements and work completed

This piece of research has presented frameworks; (i) for the selection of demand assessment methods, (ii) for the selection of LZCT assessment methods and (iii) for the selection of modelling tools for CES analysis. This has been achieved by first performing a review of MCDM techniques, and using a pre-existing method to select the most appropriate MCDM techniques to form the basis of each framework. This pre-existing method asks a series of questions regarding the requirements of the MCDM technique to be selected. For each framework, the requirements were that the selected MCDM technique was able to select the most appropriate individual or combination of methods/tools from those available.

For the demand and LZCT assessment method selection frameworks, an MCDM technique which provided a score in a global sense for each methods performance on individual criteria was required, as (i) this would allow the most appropriate overall methods to be identified, (ii) weaknesses in performance on criteria could be identified and (iii) scoring in a global sense would allow overall strength or weakness to be identified, rather than relative to the other methods being considered (as would be identified in a ranking MCDM technique). This allowed a subset of potential MCDM techniques to be identified which were then narrowed down by virtue of their strengths and weaknesses, as well as their ease of use and comprehension of the results by the Community Agent.

From the subset of potential MCDM techniques, AHP was considered to be intuitive although it required the decision-maker to have an extremely comprehensive knowledge of all options to be scored. It also had problems with consistency due to utilising a scale of preference between the options, and suffers from the well-known phenomenon of rank reversal due to utilising pair-wise comparisons. MACBETH is a similar technique which does not suffer from the problem of inconsistency but also suffers from the problem of rank reversal. TOPSIS provided no process for eliciting weights of criteria, noir checking consistency of judgements. SMARTER provides a simple process for eliciting weights which has been shown to produce results 98% as accurate as those produced through direct rating by experts; in addition the framework is simple and intuitive, although it provides no way to initially “screen” options. COTSSSP includes a simple process for “screening” options based on criteria. Certain characteristics are deemed “essential”, “desirable” or “not relevant” to a particular case study. Options are then discounted if they do not include “essential” criteria and are then scored based on “desirable” criteria. This was deemed a simple and effective way of screening methods, especially as SMARTER has issues of scoring options very similarly when used as a screening technique.

A combination of SMARTER and COTSSSP was therefore taken forward as the frameworks for (i) demand and (ii) LZCT assessment method selection. Criteria appropriate to the selection of a method or combination of methods for the analysis of a CES were then defined, based around themes of method quality, input data and practical consideration. The criteria were “method validity”, “output suitability”, “method input data resolution”, “method input data integrity”, “process clarity” and “resource requirement”. COTSSSP was used to determine “output suitability” as “essential” in that methods were required to provide output at hourly or sub-hourly resolution; methods providing this would score 100 and 0 otherwise. All other criteria were deemed “desirable” and would be scored on a scale of 0-100 based upon scoring guidelines to aid consistency in judgement making.

For the modelling tool selection framework, tools would need to be scored based on criteria. However, tools have such a number of capabilities that the criteria required to score them would exceed the maximum number required by SMARTER. In addition, to score all of the tools based on these criteria would require an in-depth knowledge of all tools which would be resource-intensive in many situations. Therefore it was decided that a range of 51 energy modelling tools – found through literature review - would be reviewed, and criteria defined to determine their applicability to modelling a CES. Using COTSSSP as a basis for this initial screening process, the criteria could be classed as “essential” or “desirable”, with all tools featuring all “essential” characteristics being taken forward to the next stage.

From the initial 52, 13 modelling tools particularly suitable for planning level design analysis of CESs incorporating LCZTs and storage were found. Tool capabilities were then categorised and documented in a series of tables. Again, based on the COTSSSP technique, the capabilities of these tools are classed “essential”, “desirable” or “not relevant” according to the requirements of a particular case study. Tools are given a score of 2 for the inclusion of each “essential” characteristic and 1 for each “desirable” characteristic; tools without all “essential” characteristics were discounted. In this way, tools were scored and the most appropriate tool (or tools, if more than one had the same score) for the case study was found.

The suitability and limitations of the frameworks was discussed, as were the suitability and limitations of the selected methods and tools, with suggestions made for areas of improvement. Gaps were identified particularly in the modelling of thermal storage systems and their controls due to the use of simple energetic models which do not readily capture important thermal characteristics such as temperatures.

10.2. Demand Assessment Method selection framework

Through the development of the demand assessment method selection framework, and subsequent scoring of demand assessment methods, it is apparent that there are many differences between such methods. The Scottish Heat Map, for instance, is a very quick and simple to use method; available online, it provides heat demand for a given area which it gathers from a range of available existing datasets. However, the output it provides is at an annual resolution which is unsuitable for modelling a CES without manipulation, and the input data it uses can be as low-resolution as a simple building floor area polygon.

Others, such as ESP-r, require the user to input extremely detailed information on building dimensions, materials and climate so that the heat transfer between nodes can be modelled and provide an overall heat demand. It is, however, an extremely labour intensive process to model each individual building in a CES in this manner – likely infeasible for many CESs. Other methods which use data measured directly from buildings include RdSAP and PHPP; these require building survey data which is far more practical to gather but only provide heat demand at annual and monthly resolution, respectively. PHPP also provides electric demand but again, only at a monthly resolution.

Tools such as HOMER have an in-built demand profile generator which can model a generic community load with the addition of diversity in the form of random daily or hourly variability. This provides the user with a simple way of modelling either thermal or electrical load for their case study. However, it must be ensured that the load realistically matches the case study and so some local data gathering specific to the case study needs to take place to scale the generic loads. It is also hard to account for diversity and differences in user behaviour without direct measurements. This is also the case with libraries of generic demand profiles such as those provided by ESRU and ELEXON for heat demand and electric demand, respectively. Methods such as the domestic electricity demand model attempt to model this by providing an approximation of demand for a building by synthesising the use of appliances over the course of a 24-hour period, with the user being able to select which hours each appliance is in operation. In the absence of any on-site measured data, this will be able to approximate the electric demand of a building, but again is no substitute for measured data. Whilst random variability in appliance use can be input, it cannot account for diversity or differences in user behaviour, which is especially relevant in small-scale systems.

Finally, local data gathering for the CES would usually take place. This includes investigating existing bill data, fuel purchases, heat production values (in the case of, e.g., an existing community biomass burner) etc., however this is ad hoc and there is no documented method for undertaking such measurement or gathering.

All of these methods have their strengths and weaknesses (as will all others), which is part of the reason that selecting the most appropriate method or combination of methods can be difficult. Not only do all methods have their strengths and weaknesses, but it is generally difficult to document or to have knowledge on all of these before making a decision about which method or combination of methods should be used for a particular case study. Generally speaking, decision makers usually make ad-hoc choices about which methods to use based on knowledge of the methods, available support, cost, available data for use in the methods, and applicability of the method to the problem they are attempting to solve.

The proposed demand assessment selection framework formalises the way in which the decision maker will select the most appropriate method or combination of methods for a case study. Methods are scored based on criteria, with scoring guidelines to provide consistency in scoring. To further provide consistency, criteria weighting is simplified by simply asking the decision-maker to rank all criteria; ROD weights are then used to approximate true weights. Once all methods are then scored, they are available to view in a single table so that their strengths and weaknesses can be compared. In this way it is simple to identify synergies between methods so that shortcomings in one method can be compensated for by the strengths of another.

The case study in Chapter 6 demonstrates this well; it is found that for heat demand assessment methods, no one single method scores well enough overall to be used in isolation and that a combination of methods should be used to create a synthesis of methods. The synthesised method is as follows: perform building surveys (using a method such as PHPP) to ascertain monthly heat demand for each individual building, scale generic hourly profiles from a method (such as HOMER or ESRU generic profiles) based on this demand, and then validate/scale these results using locally gathered fuel purchase or bill data. Similarly, for electric demand, no one single method performs well enough to be used in isolation and a combination of methods is therefore recommended. This is again, to use a method (such as PHPP) to perform surveys to obtain monthly individual building demand, which can then be used to scale hourly profiles (from either ELEXON or the domestic electricity demand model), and use measured data to validate/scale these.

Such combinations are ones which an experienced practitioner is likely to employ on an ad hoc basis; however, following this combination of methods has not been documented as a formal method or process for best practice in any available literature. The framework therefore formalises what was once an ad hoc process and allows decision makers to consistently make the most appropriate decision based on the available information when it comes to selecting and applying methods for CES analysis. The framework also reveals that due to strengths and weaknesses inherent in all methods, no one method performs sufficiently well to be used in isolation.

10.3. LZCT Assessment Method selection framework

Through the development of the LZCT assessment method selection framework, and subsequent scoring of LZCT assessment methods, it is apparent that there are many differences between such methods. Some, such as Renewables Ninja and HOMER, quickly provide annual power output for wind turbines at a given location, with an hourly resolution. This is based on wind turbine technical specifications and historical wind data. Such methods give a good indication of whether or not wind turbines would function under ideal circumstances at the selected location, but can be no substitute for on-site measurement which will account for local anomalies. The “Wind Resource Assessment: A Practical Guide to Developing a Wind Project” method provides this detail; in-depth detail into site selection and wind measurement mast deployment, which are used to measure winds – ideally over a year – for potential sites. Whilst such a method will give the best possible indication of project success, implementation is also resource intensive and likely unsuitable to provide a “first pass” at initial scoping stages.

It is also possible that local data gathering for the LZCTs can take place. This would include investigating any existing datasets in the area, as well as local CESs or relevant LZCTs that are in operation nearby. This is, however, ad hoc and there is no documented method for undertaking such measurement or gathering.

Methods for analysing LZCTs have their strengths and weaknesses, which is part of the reason that selecting the most appropriate method or combination of methods can be difficult. Not only do all methods have their strengths and weaknesses, but it is generally difficult to document or to have knowledge on all of these before making a decision about which method or combination of methods should be used for a particular case study. Generally speaking, decision makers usually make ad-hoc choices about which methods to use based on knowledge of the methods, available support, cost, available data for use in the methods, and applicability of the method to the problem they are attempting to solve.

The proposed LZCT assessment selection framework presents a formalised, simple and intuitive way for the decision-maker to select the most appropriate method or combination of methods for the case study at hand. Methods are scored based on criteria, with scoring guidelines to provide consistency in scoring. To further provide consistency, criteria weighting is simplified by simply asking the decision-maker to rank all criteria; ROD weights are then used to approximate true weights. Once all methods are then scored, they are available to view in a single table so that their strengths and weaknesses can be compared. In this way it is simple to identify synergies between methods so that shortcomings in one method can be compensated for by the strengths of another.

The case study in Chapter 7 demonstrates this well; it is found that the highest scoring method – "Wind Resource Assessment: A Practical Guide to Developing a Wind Project" is the highest scoring method but fails under the "requirement for resources" criterion and must this be discounted. Failing on this particular criterion cannot be mitigated for, so the most appropriate method for the case study was a synergistic combination of Renewables Ninja and Local data gathering. For this case study, there was long-term data available from wind turbines in operation on the island. This data can therefore be used in combination with that from Renewables Ninja to create a synergistic combination of methods. Renewables Ninja would be used to create an annual profile which could be scaled on a daily/weekly/monthly basis based on the measured data; gaps in the measured data could then be accounted for. An experienced practitioner is likely to employ such a method on an ad hoc basis; however doing so has not been documented as a formal method or process for best practice in any available literature. The framework therefore formalises what was once an ad hoc process and allows decision makers to make the most appropriate decision on all available information when it comes to selecting and applying the most appropriate LZCT assessment methods for CES analysis.

10.4. Modelling Tool selection framework

Through the categorisation and documentation of modelling tool capabilities, and application of the MCDM modelling tool selection framework, it is apparent that there are many differences between tools. Some tools, such as EnergyPLAN, combine all energy sectors based on the view that holistic consideration across sectors leads to optimal solutions. Other tools are primarily single domain focussed, e.g. iHOGA has strong capabilities for electrical analysis with a wide range of storage models but no thermal capability.

Design optimisation capabilities in the tools generally optimise for financial or technical considerations. Only iHOGA optimises for human considerations (human development index, job creation) and two tools optimise for environmental considerations. Much work has been done on external optimisation used in a two-step process. This may influence the lack of embedded optimisation options in the tools; another factor is the preference for the simplicity and transparency available in full factorial parametric analysis.

The review identified a lack of detailed district heating modelling capability in any of the community-scale tools, with only a heat loss parameter as input, factors such as the heat demand density, distribution temperatures, network layouts and controls which have a large effect on ancillary energy use and losses in district systems are not directly addressed.

Analysis of controls modelling capabilities in the tools showed a wide range including operational optimisation, fixed order, and user-defined orders, for dispatch of supply and storage. Operational optimisation control is usually used with a cost based objective function, other possible objective functions such as maximising local use of renewable generation, minimising grid imports or minimising emissions are not generally directly supported, with DER-CAM a notable exception. More advanced predictive controls based on weather forecast and demand prediction are not supported, although the non-chronological operational optimisation in EnergyPRO and the deferrable load functionality in HOMER etc. can represent this type of control but with significant simplifications. The option to run tools in combination with external control algorithms in separate software packages is one way round this limitation.

The tools, with the exception of DER-CAM, focus on load shifting and use of storage where there is grid connection to optimise value based on cost (arbitrage) while it is widely accepted that other grid services (such as frequency stabilisation, peak reduction, avoidance of capital investments etc.) may also be very important.

The review of storage functionality and modelling revealed frequent use of the simple storage model. More complex models for electrochemical storage exist particularly for use with lead-acid, li-ion and flow batteries. Thermal storage is limited to simple energetic models which do not directly take account of temperature variations other than in assessing capacity. These may be suitable for initial planning design stages but have limitations. To take account of temperatures, heat transfer rates, stratification, and phase change in thermal stores necessitates more complex models. It would appear that these will be required in the future to support realistic modelling of the hybrid systems and advanced controls for which these parameters have critical importance.

There were few tools found to be directly capable of analysing fuel synthesis technologies, such technology, however, is currently unlikely to be at a community scale in the short term. For this reason tools developed for regional scale have most capability.

The wide range of tools available and their differing capabilities makes a capability categorisation and tool selection process of value to the end user of such tools, and also of use to inform those looking to expend effort or resources in modelling of such systems. The abundance of available tools and rapidly developing field dictated that it was impossible to include every one. A thorough literature was performed and so at the time of writing their selection is representative of the state of the art in tools for planning-level design at community scale.

The MCDM modelling tool selection framework presented is not limited to the tools identified here but is intended to provide a framework which can be used in future to refresh the capabilities categorisation or be applied to further tools. The review of required capabilities as the first part of the selection process can also form a guide for modellers to ensuring relevant factors are considered. More detailed scoring systems in the selection process would be possible however to score each tool on a scale of 0-100 based on performance of criteria, as opposed to the relatively simple measure of inclusion of essential and desirable characteristics, would be resource intensive.

10.5. Limitations and future work

One weakness of the demand and LZCT assessment frameworks is that, due to being primarily based upon the SMARTER MCDM technique, they require the decision-maker to have a reasonably intimate knowledge of the methods in order that they are scored effectively. This has the result that the decision-maker must invest a reasonable amount of resources in developing this knowledge, which may be a challenge, depending on available resources. This problem could be mitigated for if, instead of requiring the user to judge the methods based upon their performance on criteria, they were judged based upon their inclusion of certain features or qualities, and the importance of these to the case study. This is the basis of the COTSSSP technique; the principals of which were used to capture the "essential" requirement for methods to provide an output at hourly resolution or less. Methods fulfilling this criterion scored 100, otherwise they scored zero. The same principle could be applied to all method capabilities; all method capabilities being categorised and documented and then deemed "essential", "desirable" or "not applicable" according to the requirements of the case study. This would bring the demand and LZCT assessment method selection frameworks in line with the modelling tool selection framework, unifying the overall process. Whist this would simplify the process, subtleties in scoring would be lost and the frameworks would be far less capable of identifying synergistic combinations of methods. In the case study example, synergetic combinations were easily identified as methods with low scores could be mitigated for through combining them with methods with higher scores on the same criteria – this would be far less likely if criteria were binary yes/no regarding the inclusion of certain capabilities.

For example, "Input data integrity" is made up of three sub-criteria: "data measurement period", "data accuracy" and "data reliability". If a method were to be scored in a binary way based upon their inclusion or not of certain capabilities, these sub-criteria would likely be transformed to:

- "Is the data measurement period over one year or more?"
- "Has the data been validated to be accurate?" and
- "Is the data from a reputable source or been measured on-sire by experts?"

Both PHPP and Local data gathering would receive a binary "yes" score for these sub-criteria and thus any subtlety in their differences would be lost. This would result in the framework failing to identify the synergistic combination of methods which were identified through expert scoring using a scale and scoring guidelines. For example, in the case study, this would have meant that Renewables Ninja and the Local data gathering methods would have scored identically, and there would have been no apparent benefit through combining them.

A recommended area for future work is to investigate the categorisation and documentation of demand and LZCT method capabilities, in order that the process for scoring of each method is simplified. This would form the basis of demand and LZCT method selection frameworks which require less expertise to implement; rather demand and LZCT assessment methods would be scored on their inclusion or omission of certain capabilities. Whilst this would result in more clear and simple frameworks, there is potentially a danger that the subtleties captured by expert scoring in the frameworks developed in Chapters 5 and 8 may be lost. The differences between these frameworks would need to be analysed in future work to draw any conclusions on this.

Likewise, the possibility of the MCDM modelling tool selection framework being more complex and employing a scoring system based on expert analysis and opinion is a recommended avenue for future work. As the framework developed in Chapter 8 stands, tools are scored in a simplistic way on their inclusion/omission of certain capabilities. This does not capture any subtleties in the differences in performance different tools will have on criteria; either they receive a score for their inclusion of a capability, or they score 0 for their omission of said capability. Scoring the tools on the way in which they e.g. model a certain criterion *is* covered to an extent with tools scoring more highly (if a requirement of the case study) for more complex modelling of thermal and electrical storage, but not on other criteria. If this were extended to all criteria then the differences in performance on criteria could be evaluated, and hence synergistic combinations of tools identified – an important point, as in real-world ”ad-hoc” modelling situations, combinations of tools are frequently used. If developed, such a framework could be contrasted and compared with the modelling tool selection framework developed in Chapter 8 to draw more robust conclusions.

The more detailed simulation modelling tools currently used in buildings and systems domains have potential to be developed for community scale energy systems in future, allowing more physical detail to be captured in planning level design studies; their capabilities could also be assessed and tools selected using the same process.

An element not considered here is the validation of the demand and LZCT assessment methods and modelling tools. So far in available literature case studies are largely based on design and do not include monitored data on completed schemes that include DSM and storage. Experience in the buildings industry has found that performance gaps are common [278] and identified that industry process needs to evolve to address these gaps [279]. It is critical that similar issues are addressed to avoid performance gaps in future community scale energy systems; this would be achieved via performance monitoring.

The main contribution of this work is to show the applicability of the frameworks, which replace current ad hoc processes. It is acknowledged that the frameworks themselves are not finished articles, and that they require further refinement and through iterative use and development by others; it is envisioned that once this work has been undertaken, their use could be codified through industry standards such as CIBSE so that they could be consistently applied to a given situation.

Once the above is completed, it is envisioned that the frameworks could be developed into a user-friendly tool and tested in a real-word scenario through collaboration with consultants working with communities implementing CESs. In this way, the frameworks can be tried and tested, and compared with the way in which such professionals currently undertake CES analysis. Further work could involve full validation of the frameworks through application to case studies, with monitoring taking place of the implemented system to compare with predicted results from methods and tools selected by the frameworks. In this way, performance gaps between modelling and actual results can be documented and interrogated.

11. Chapter 11 - Conclusions

11.1. Conclusions

Modelling is required to assess the best possible solution for a CES; this requires input information on energy demands and LZCTs including storage and demand side management. Several methods exist to provide such inputs; however these vary greatly and before this research, there was no defined way to select the most appropriate methods for a case study. Modelling tools(s) must also be selected to analyse inputs provided by these methods to provide an analysis of a case study. There are many modelling tools which vary in quality, capability, resource requirement and relevance; again, before this research there was no way to select the most appropriate tools(s) for a case study.

This research has successfully developed frameworks to select (i) energy demand assessment methods, (ii) LZCT assessment methods, and (iii) CES modelling tools.

Parts (i) and (ii) considered the available methods for energy demand and LZCT analysis, respectively, identifying the best method or complementary synthesis of methods for use on a case study. These frameworks were based on a combination of the existing SMARTER and COTSSSP MCDM techniques. The combination was selected so that criteria relevant to the selection of demand and LZCT assessment methods could be defined; these are then able to be ranked, weighted and scored according to SMARTER according to the requirements of the case study. The inclusion of COTSSSP in the frameworks allows the scoping out of methods which do not meet certain criteria, and the identification of possible syntheses of methods. These frameworks were then demonstrated for a case study.

Part (iii) considered the modelling tools available for CES analysis, identifying the best tool(s) to use for a given situation. Capabilities of tools for CES analysis were categorised and documented, and then a selection process based on COTSSSP was defined. Using this framework, tool capabilities are classed as “Essential”, “Desirable” or “Not applicable” to the case study. Tools without essential capabilities are eliminated, and tools are scored based on their inclusion of “Essential” and “Desirable” criteria. This allows a sub-set of tools to be selected for further consideration. This framework was then demonstrated for a case study.

The frameworks provide an ordered and logical process in contrast to current ad-hoc approaches and are a useful addition to aid modelling of future CESs. The frameworks were discussed in relation to their applicability to the analysis of a CES, limitations of the work identified and recommendations made for future work.

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