Ref. Ares(2020)1266822 - 28/02/2020

RUGGEDISED
Designing smart,
resilient cities for all

EUROPEAN COMMISSION
Horizon 2020
H2020-SCC-2016
GA No. 731198

Deliverable No.	RUGGEDISED D1.5	
Deliverable Title	Prototype smart energy district planner	
Dissemination level	Public	
Lead participant	TNO	
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Status	Final	28-02-2020

H2020-SCC-2016 – Grant Agreement number 731198 - RUGGEDISED

Acknowledgement:

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

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Disclaimer:

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 731198. The sole responsibility for the content of this document lies with the RUGGEDISED project and does not necessarily reflect the opinion of the European Union.

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Executive Summary

The RUGGEDISED project team are designing and delivering a wide portfolio of smart solutions to improve sustainability in their cities. The delivery of these projects is often being guided by input data from modelling tools. This is required, as in many cases the smart solutions are complex and multi-faceted systems, and performance information from modelling and simulation can be used to guide the decision-making process as a smart solution design develops over time.

This report contains the “prototype smart energy district planner” (SEDP), which is essentially a set of analytical tools and a framework for their application that have evolved along with the development of the smart solutions in the lighthouse cities. This guide is based on the lessons that has been learned and discussed by the Lighthouse Cities in the RUGGEDISED Liaison Group meetings. Together with D1.4 “Guide for setting up and sustaining Local Innovation Platforms”, D1.6 “Guide on Smart City Design and Decision Platform” and D1.8 “Guide on ruggedized implementation and innovation of smart solutions” this guide synthesises the lessons learned from the implementation phase of the RUGGEDISED project. The RUGGEDISED Fellow Cities, will test the collaborative smart city guides. Eventual changes will be taken up in final versions of the guides at the end of the running periode of the RUGGEDISED project (Autumn 2021).

The different smart solutions emerging from the cities are reviewed along with different approaches to the evolution of designs (using buildings as an example). A tool-driven design approach is presented and adapted to suit an environment where the solutions being developed are prototypical, as the case with RUGGEDISED. This entails that the technologies and technology combinations are often not tried and tested, and consequently a significant amount of iteration is required as the different smart solutions progress.

The iterative process outlined, hinges upon decision points, where these points involve 4 key elements 1) the criteria against which decisions are made; 2) the data required to assess performance against citeria (and potentially pass on to the next evolution of the design; 3) the tools required to generate the required performance data; and finally 4) the people (stakeholders) required to arrive at a decision with regards to the next stage of the process.

Each of these 4 elements are elaborated in some detail including: the different types and mixes of criteria against which decisions can be made (technical and non-technical); types and sources of data (not all of which may come from modelling) along with possible destinations for data generated aside from the immediate design process; the appropriate use of tools for decision support and types of tools are reviewed; and finally the identification of the stakeholders required to make decisions is elaborated on.

Examples where tools have been deployed in the development of smart solutions in each of the the three lighouse cities are provided along with the context of their application relation to the SEDP. These are the Rotterdam heat network, Glasgow smart charging hub and Umeå smart office solution.

The report highlights how tools and modelling are still applicable once smart solutions have been realised, in that modelled performance data can be used to gauge real-world performance. Further data from technology performance monitoring can be used to improve the developed models for use by other teams.

Finally the major beneficiaries of the work and experience distilled in this report are the fellow cities, allowing them to learn from the lighthouse cities’ experiences and providing them with the means

(through use of the developed tools and processes) to make more robust design decisions with regards to the development of their own smart solutions.

1. Introduction

RUGGEDISED is a smart city project funded under the European Union's Horizon 2020 research and innovation programme. It brings together three lighthouse cities: Rotterdam, Glasgow and Umeå and three fellow cities: Brno, Gdansk and Parma to test, implement and accelerate the smart city model across Europe.

Working in partnership with businesses and research centres, these six cities will demonstrate how to combine ICT, e-mobility and energy solutions to design smart, resilient cities for all. This means improving the quality of life of citizens, reducing the environmental impact of activities and creating a stimulating environment for sustainable economic development.

A key outcome from RUGGEDISED is developing decision support tools and processes, derived from the experiences emerging from the smart energy solutions in the partner cities.

This report establishes the basis for a prototype smart energy district planner (SEDP)[1] that comprises the generic process, and specific tools, tasks, information and stakeholders required to develop and evaluate a smart solution for a sustainable city district. This report aims to consolidate the learning from the diverse design activities occurring in RUGGEDISED and establish the template by which partner cities and others could develop and evaluate their own smart city solutions. This guide is based on the lessons that has been learned and discussed by the Lighthouse Cities in the RUGGEDISED Liaison Group meetings. Together with D1.4 "Guide for setting up and sustaining Local Innovation Platforms", D1.6 "Guide on Smart City Design and Decision Platform" and D1.8 "Guide on ruggedized implementation and innovation of smart solutions" this guide synthesises the lessons learned from the implementation phase of the RUGGEDISED project. The RUGGEDISED Fellow Cities will test the collaborative smart city guides. Eventual changes will be taken up in final versions of the guides at the end of the running periode of the RUGGEDISED project (Autumn 2021).

2. Smart City Solutions

The three lighthouse cities are developing a diverse range of smart solutions centred on low carbon energy systems, transport and the use of ICT to enhance sustainability. A brief overview of these solutions is provided here (adopted from the Implementation Reports (D2.6, D3.4 and D4.6) developed by the Lighthouse Cities).

2.1. Rotterdam

- R1 Geothermal seasonal heat and cold storage - the geothermal head-cold storage and heat pumps connect the large buildings in the area to one thermal grid. This means enabling local heat and cold exchange with a lower use of energy and lower total cost of ownership. Each building will have a heat pump to meet the heat requirement. The waste heat of the condenser is fed back into the heat-cold storage. High temperature cooling is provided directly from the smart geothermal grid.
- R2 Thermal energy from waste streams - in addition to the above, the use of other thermal waste streams (RES) will be stimulated as much as possible by making further connections to the thermal smart grid. On the district scale, the district sewage water from nearby households is used to distract heat or cold for use in the smart grid. Depending on the need it can be used directly, or stored for a season, regenerating the storage and create a thermal balance.
- R3 Surface water heat/cold collector - solution was geared to facilitate heat/cooling recover in sewer. The analysis showed that the solution is not economically feasible, therefore, the solution will not be implemented.
- R4 Pavement heat collector - a pavement heat collecting system in combination with the Smart Thermal Grid in the Heart of South area. The pavement heat collector (ca. 400m2)

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[1] This deliverable D1.5 corresponds with the deliverable description D1.6 from the Description of Work. Unfortunately, the numbering and description of deliverables got mixed up.

will be relocated to the back of the Ahoy exhibition complex. The realisation can be combined with the re-paving of an existing asphalt road. Also, a heat exchanger can be placed, so the heat and cold can be fed back into the Thermal Smart Grid and can be stored in the heat-cold storage system

- R5 DC grid, PV and storage for mobility - the existing grid at the bus station cannot provide enough power for fast charging of the RET electric buses. RET will place PV's on the roof of the bus- and metro station in order to deliver the energy directly from the grid into the charging points of the buses.
- R6 Smart charging parking lots - reduce the peak loads by introducing smart charging at parking lots. The negotiations with Ballast Nedam/Heijmans, to install several charging stations in the new to be build parking garage, are ongoing.
- R7 Optimising e-bus fleet - which focuses on the replacement of conventional diesel buses with battery-powered electric buses at RET. RET tested the reliability of the ICT software in real time to experience the effects on the complex logistic operations. In close collaboration with RET, both the simulation model and the optimization model have been tested for a fleet of 50 electric buses to be charged at the Heart of South bus terminal, which are planned to be in operation at the end of 2019. The first results show that under planned conditions the schedules are feasible, but are not sufficiently robust against delays. For this, re-optimization during the day will be necessary. Currently, we are in the process of adapting the models to allow re-optimization, based on real-time data.
- R8 Energy management - this innovation involves the implementation of energy- and building software (Simaxx) at the Ahoy Complex (in close collaboration with Eneco, the electricity producer & supplier). This implementation is still work in progress. Ahoy will be the first building using this software. The creation of the innovative dashboard is still work in progress. A first version is expected after the summer of 2019.
- R9 3-D city operations model - the development of the 3D city operations platform is an iterative process of learning by understanding and learning by doing. Learning by doing is done by building a platform and learning through evaluation of every step taken. The 3-D city operations model will act as the Heart of South's digital twin.
- R10 Lo-Ra smart network - LoRa (Long Range) is a low-power wide-area network (LPWAN) technology. This Internet of Things connection has specifically been developed to exchange small amounts of data between objects and systems. The network is meant for equipment which does not constantly need its own internet connection. The LoRa solution was implemented in the beginning of the RUGGEDISED project but caught by the "law of the handicap of a head start. The two solutions 'efficient and intelligent street lighting and 'Smart Waste Management' did, in the end, not to make use of the existing LoRa network.
- R11 Smart street lighting - the Smart Street lighting poles are equipped with a tele-management system and LED lights. From a distance they can be controlled, monitored and give insight in their energy use. The energy use data can be fed into the 3D model of the digital twin to provide insight in their performance.
- R12 High performance servers in homes - high performance servers in residential buildings (built by Ballast Nedam), could provide highly distributed computing power (computing facilities, data centres) while, at the same time heating homes for free and drastically reducing overall CO2-emissions. Unfortunately, Nerdalize were declared bankrupt due to a lack of sales growth and the necessary additional funding in final quarter of 2018.
- R13 Smart waste management - which is focused on the 6,500 underground waste containers. The so-called 'filling degree meter' in the waste container measures every hour how full the container is. Based on this information, the system determines when the container can best be emptied. The routes for the drivers are automatically generated, based on the collected data, a so called 'dynamic route planning'

2.2. Glasgow

- G1 Heat and cold exchange – which focuses on the connection of different client types to a district heating network, including public bodies Glasgow City Council and the University of Strathclyde, the private Tennents brewery and public, social housing. The work involves developing appropriate technical and business models to facilitate interconnection.
- G2 Deployment of a suitable battery storage technology – this involves the deployment of Lithium ion batteries to support the integration of renewable energy sources such as PV and small-scale wind in Glasgow smart street and to support dynamic energy exchange across the local network, e.g. facilitating the charging of electric vehicles using power from photovoltaics or combined heat and power (CHP).
- G3 CHP surplus power storage in EV Charging hub battery storage – where combined heat and power (CHP) devices feeding the heat network can also supply surplus energy to local energy demands such as battery-supported EV charging.
- G4 Optimisation of the integration of near-site RES – where renewable energy systems (RES) are integrated into the local electricity network; these include a photovoltaic (PV) canopy on a city centre car park and small-scale wind turbines.
- G5 EV Charging hub in city centre car park – which involves developing a dedicated EV charging hub is co-located at the car park along with battery storage and the PV canopy.
- G6 Intelligent LED streetlights – which involves re-lamping the streetlights in the RUGGEDISED smart street with LED lamps, integrated EV charging functionality, air pollution monitors and installing a wireless communications network (for energy management and real-time pollution monitoring).
- G7 Smart open data Decision Platform/central management system
- G8 Implementation of demand-side management technology in street lighting, in domestic and in non-domestic properties

2.3. Umea

- U1 Connection to 100% Renewable Energy - The purpose of the solution is to develop a new business model to make it possible to share excess renewable energy between stakeholders in a value chain and ensure better usage of geothermal storage. The overarching goal is to help the stakeholders reduce their climate impact and lower the costs of energy.
- U2 Peak load variation and peak power control - An automated peak load management system which uses buildings as thermal energy storage hubs, so that stored energy can be used at peak periods when the need for energy is at its highest.
- U3 Geothermal storage - Simulation of geothermal storage for seasonal storage of heat.
- U4 Intelligent building control and end user involvement - An intelligent and integrated control system for the internal climate will be installed in new apartment buildings (Lilljansberget) in the University City demonstration area, with the potential to allow for the continuous analysis of energy performance as well. The offices will be connected to a monitoring system where settings can be managed and the status reported and stored.
- U5 Climate smart bus station - The climate-smart bus station is a new type of bus stop is expected with its innovative design - where technology, people and the environment interact with each other to reduce the city´s environmental impact and its carbon dioxide emission - to act as a symbol for the Smart University District. The bus stop is served by both electric and fossil fuel buses.
- U6 E-charging infrastructure hub - The overall aim for the e-charging hub is to develop it in into an “Energy-hub”, different batteries and storage solutions within this solution as well as a smart power control management-system, including a dynamic payment system for the charging, will be tested.
- U7 Smart business model for flexible parking - To help manage air quality in the centre of Umeå, the local authority has decided that no new workplace parking places shall be built in the central urban area. In order to enable more sustainable travel to and from the building, property developers are offered the possibility of a reduced fee on the cost of the

parking pay-off fee through the business model called “Green Parking Pay-off”. The developer signs an agreement in which they agree to implement measures to support sustainable travel for the users of the building.

- U8 Smart Open Data City Decision platform - The smart city open-data decision platform, aims to provide real-time visualisation as well as static data to show the impact of smart city interventions.
- U9 Demand-side management - The Demand Side Management system, logs sensor data from different sources and aggregates it into one platform. The collected data will be used as the baseline when setting up a new kind of analysis tool in which the building’ status will be analysed and visualised. Currently, 1000 sensors have been installed in one of the university buildings.

2.4. Discussion

Whilst the portfolio of smart projects listed is tailored to each of the individual cities, there are significant areas of commonality between the city projects; this allows for comparative learning between similar city solutions and the re-use of tools developed and/or applied by one city on another city’s project. Solution themes and their technical linkages are illustrated in Figure 1,.

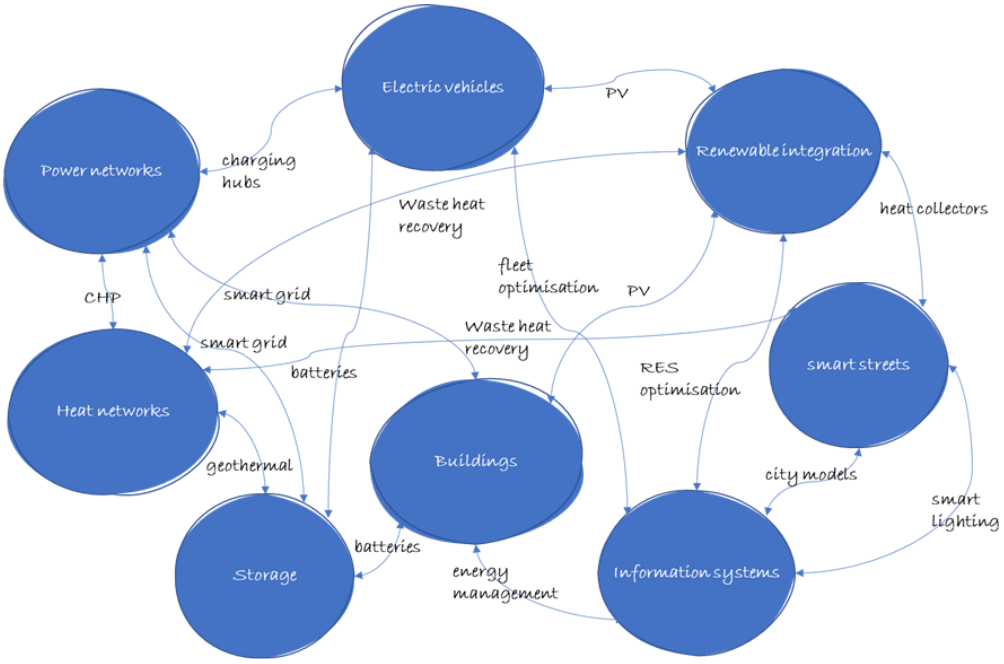

Figure 1: common themes for RUGGEDISED smart solutions and linking technologies.

3. Supporting Smart Energy Solution Design

RUGGEDISED involves the development of leading-edge, low-carbon smart solutions, featuring combination of technologies within a city environment. However, this an intrinsically complex design challenge in that 1) the smart solution systems are dynamic as their state changes with time; 2) their behaviour is typically non-linear, e.g. a small variation in the system environment state can lead to a significant change in its state; 3) there are stochastic elements in each smart solution, e.g. where there is uncertainty in demand and supply of energy or use of transport; 4) the solutions are systemic in that all of their different constituents elements interact and also interact with the city around them.

Further, the smart solutions being trialled involve technologies or combinations of technologies which are new or unfamiliar to the wider design community. Consequently, simulation and modelling is being used extensively within RUGGEDISED to support the design and development of the smart solutions, enabling the city teams to gain insight into the likely behaviour of a smart solution prior to installation and to (usually iteratively) evolve a design through its various stages.

Here, a “prototype smart energy district planner” (SEDP), is elaborated. Effectively this is guide for EU cities, illustrating how modelling and simulation fit in to a wider, tool-driven, smart systems planning and design process (Figure 5). Effectively the SEDP is the combination of tools, data, criteria, people and processes required to evolve a smart solution design, allowing the city design team to make data-informed design progression decisions, and reducing the risk that the solution will fail to deliver its intended outcomes.

The SEDP concept has evolved as the project has progressed, and that has been distilled from the partner’s experiences of using modelling to support the evolution of their solutions. It illustrates a form of organic, iterative design process, which relies on the application of modelling to provide performance information.

It should be noted that the process illustrated in Figure 5 also looks beyond just modelling and data and considers *who* should be involved in progressing smart solution concepts.

3.1. Existing Design Process Concepts

There are already a variety of iterative design process concepts in the literature that attempt to depict the path of a design process. For example in the UK, the RIBA[2] plan of work (Sinclair, 2013) attempts to depict how a building design progresses over time. However, it does not specifically define how modelling tools, and the feedback on likely design performance that they provide, can be used within the design process. Further, the concept diagram of Figure 2 seems to suggest that design is a smooth progression, whilst in reality, particularly when new technology combinations are being trialled, there is often significant iteration within and between the stages.

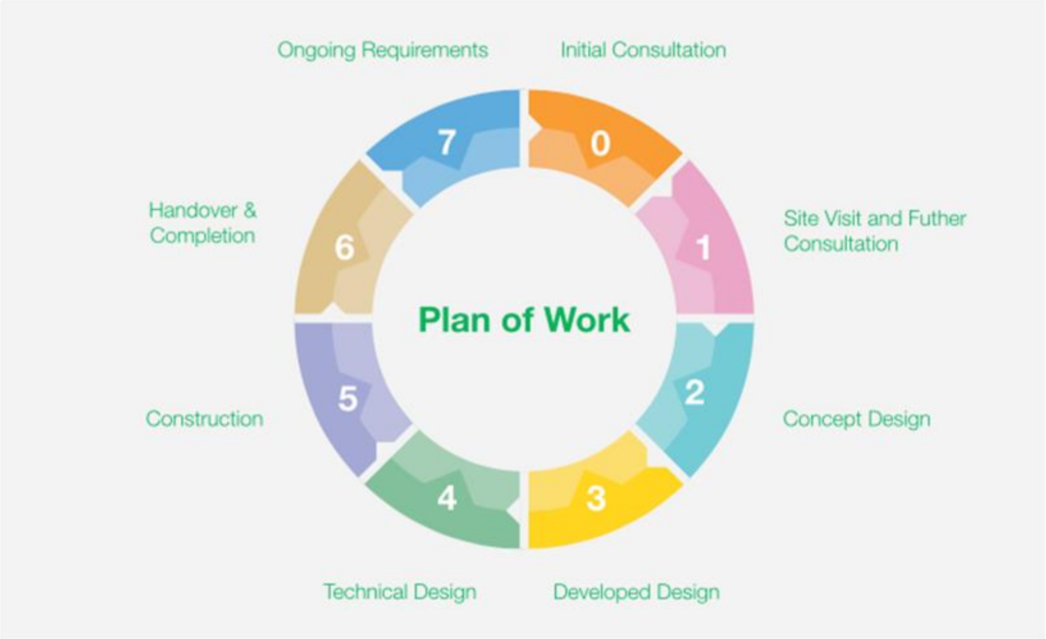

Figure 2: RIBA design stages (from architectureforlondon.com).

Other organisations such as the American Institute of Architects produce guidance on the use of modelling (particularly energy modelling) within the design process (AIA, 2019). Others such as McElroy and Clarke (1999) revised the entire design process to be one guided by modelled outputs at each stage.

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[2] Royal Institute of British Architects.

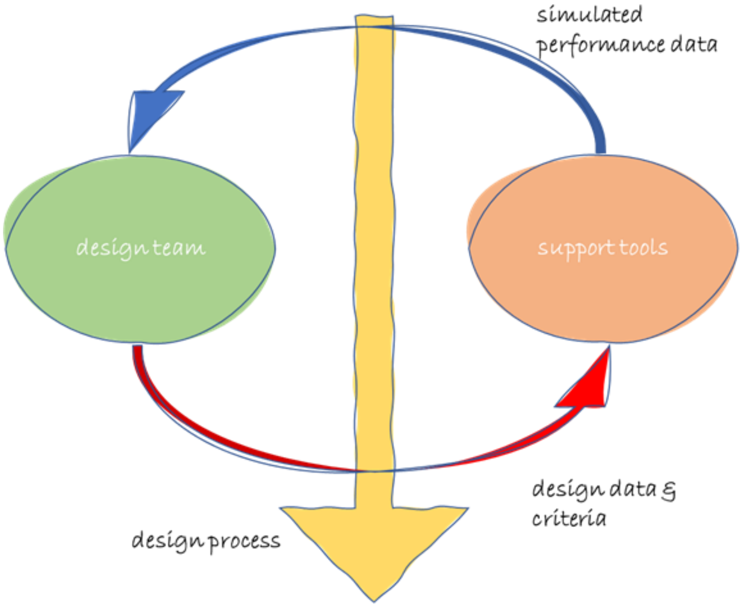

Figure 3: Tool-based design (after McElroy and Clarke, 1999).

3.2. Prototype Smart Energy District Planner

The smart energy district planner outlined here draws from both formalised design stages and more iterative, tool-assisted design processes. However, it expands the scope of the process description to include the *people* required to make robust decisions, based on the data emerging from concurrent design and modelling processes.

The real value added from this RUGGEDISED process is at the decision points of a design process i.e. those points where a concept either proceeds to the next stage of development, is rejected or requires revision, based on the outcome of (typically) a computational analysis. Each decision point involves four key elements:

1) the *criteria* against which performance is being judged;

2) the *people* needed to make a robust decision;

3) the modelling *tools* required to support the process and;

4) the performance *data* required to compare performance against the specific evaluation criteria (a subset of which can inform the next stage of the design process).

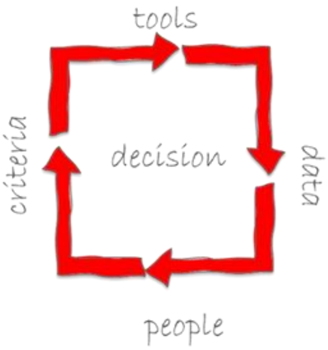

Figure 4: elements of a decision point.

These elements combined help reduce (but does not eliminate) risks, including design time being wasted on a weak or inappropriate design solutions and ultimately of a smart solution performing poorly when physically realised.

3.3. The Design Pathway for Smart Solutions

A design process is more than a single decision point and typically involves the evolution of a design concept with time. As the design progresses the design becomes more refined and the data and models available to the design team to make decisions are richer. The figure below illustrates how the decision could points fit within a typical project design flow path for a smart energy solution, starting from a rough set of concepts, through the more detailed stages of design.

Note that, as the smart solutions analysed within RUGGEDISED are often prototypes and design teams may be unfamiliar with technologies or technology combinations, the design process from concept from final design may be highly iterative; this is reflected in the path of Figure 5.

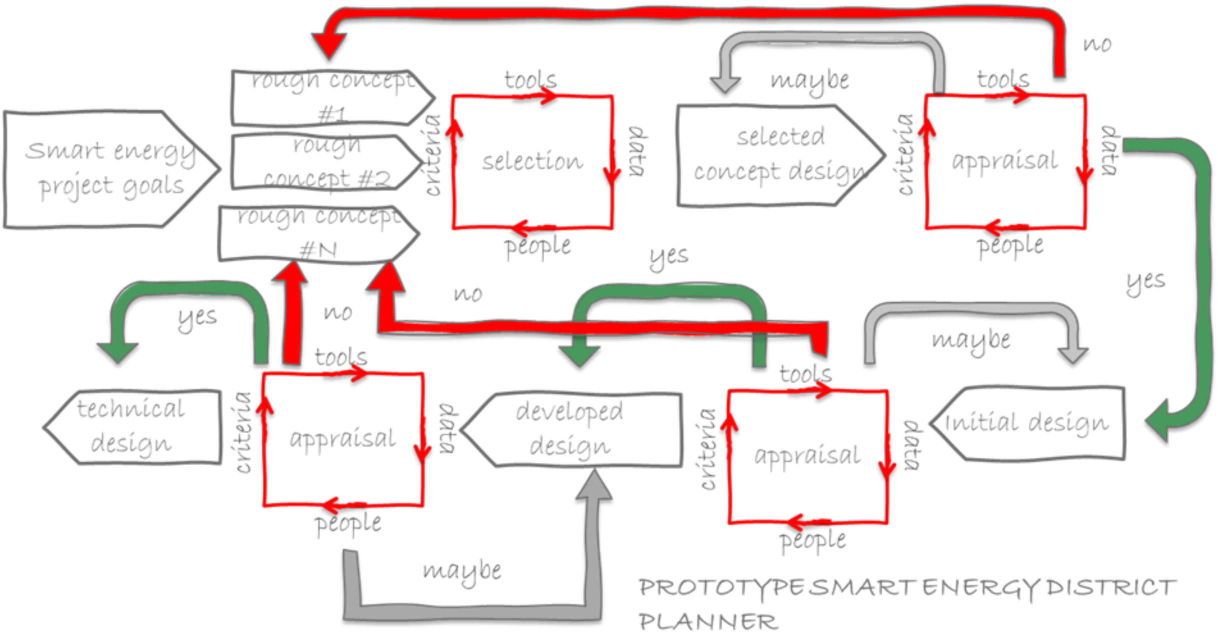

Figure 5: Illustrative process design path.

3.4. Decision Points and Iteration

The decision points occur at the end of a stage of the design process. Typically, this would involve identifying the specific performance criteria that the design would be required to meet; generating a model; simulating to obtain performance data and then an appropriate team evaluating the modelled performance against the performance criteria. Experience during RUGGEDISED has indicated that the course of the path of the process is not always linear. Depending upon the decision process, the design can proceed to the next stage, iterate the current stage to improve performance through design changed; or return to an earlier stage of the process if performance cannot be improved by a simple design alteration, or where the original concept requires a re-think.

The following sections provide more detail on the four elements of the decision points of Figure 4: people; criteria for decisions; tools and data.

4. People (stakeholders)

Data and performance evaluation are important; however, it is also critical to have the right people available to decide.

“Social and technological innovation should be a unity of two parts that complement each other”. This was stated by the High-Level Panel of the European Decarbonisation Pathways Initiative in its final report (2019, p.140). Dealing with innovative projects inherently means dealing with complexity and uncertainty. Local government and its (semi)private partners are confronted with so called complex (environmental) problems, sometimes even characterized as “wicked” (Head & Alford, 2015) or “super wicked” (Levin et al., 2012) problems. In the Innovation and Implementation Framework (deliverable 1.2, 2017) the RUGGEDISED Lighthouses collaboratively defined stakeholder strategies to deal with such wicked problems. The following stepwise approach towards involving stakeholders in smart city projects is adapted from this co-creative effort.

“Wicked problems are generally seen as associated with social pluralism (multiple interests and values of stakeholders), institutional complexity (the context of inter-organizational cooperation and multilevel governance), and scientific uncertainty (fragmentation and gaps in reliable knowledge)” (Head & Alford, 2015). In addition Funtowicz and Ravetz (adapted from Van der Sluijs, 2012) provide a very helpful typology of complex (environmental) problems by distinguishing 6 typical issues that decision makers have to face in complex policy making situations:

- Decisions should be made in an early stage, before enough scientific evidence is in place
- The error costs of decisions are high
- Many different values, and values are in dispute
- Large uncertainties within the knowledge base
- Assessment dominated by models, scenarios and assumptions
- Many hidden value loadings in problem frames, assumptions and chosen indicators.

Such wicked problems, which include smart city development, require decision-making processes that take into account pluralist and self-organizing networks of interdependent governmental, private, non-governmental, and societal actors. Controlled top-down decision making within neatly confined governmental structures are no longer appropriate to answer the challenges faced. There are several reasons why we should involve stakeholders. In complex environmental problems responsibilities, knowledge and power are distributed among the involved actors: governmental bodies, businesses, and stakeholders. This gives already the answer why we should involve stakeholders in the policy process: because they are responsible for certain aspects of the environmental problem, because they have certain knowledge that should be brought into the process, or because they have a certain power: power to obstruct or power to realise.

4.1. Identifying the Right Stakeholders

The core[3] of stakeholder involvement is that governments develop policies from an early stage in consultation and co-operation with stakeholders. Edelenbos (2000) defines stakeholder involvement as "the early involvement of individual citizens and other organized stakeholders in public policy-making in order to explore policy problems and develop solutions in an open and fair process of debate that has influence on political decision-making" . Stakeholder involvement as a process differs from traditional public consultation procedures in that stakeholders are involved early enough to influence policies when they are formulated. It makes sense, thus, to involve stakeholders in policy problems that are complex, and we should do that from an early stage of the policy process, i.e. when the problem is framed.

Who are the stakeholders?

To identify the stakeholders a stakeholder analysis can be performed. In this stakeholder analysis one should make a list of all people and organizations who influence the policy problem or who can help to solve it. After identifying the most important stakeholders one should identify the

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[3] The following section is adapted from Slob, A. (2010)

interests and goals of these stakeholders in the process by interviewing them. For each stakeholder the following questions should be answered:

- What will the stakeholders contribute to the process?
- What kind of knowledge do they possess?
- What are the relevant interests and goals of the stakeholders?
- How do the stakeholders interpret the issue at hand?
- How well informed are the stakeholders about the issue?
- What are the (possible) motives for these stakeholders to participate, or not to participate?

Stakeholders do not necessarily share the same view or perspective (Thompson et al.,1990; Schön and Rein, 1994) With perspective we mean the set of values through which the world is perceived, and that causes to interpret situations and occurrences differently.

4.2. Stakeholders for Goal Definition

First we need to know what kind of role we want to give to the stakeholders. Do we only want to inform them or do we want to engage them in the policy making process? According to Gerrits and Edelenbos (2004), involvement of stakeholders in policy processes can be arranged from low to high involvement:

- Information: providing information to the stakeholders
- Consultation: consult stakeholders to hear what they think that must be done
- Advising: stakeholders give advice about the policy or measures that should be taken. And their recommendations should be taken into account by the policy organisation
- Co-producing: stakeholders are regarded as equal policy makers but decision-making remains in the political domain
- Co-deciding: decision-making power is handed over to stakeholders.

The process itself should be designed in an open and transparent way by professionals who are used to design these processes. It should be divided into logical steps (for the stakeholders) and contain stakeholder meetings. This process design, together with their role in the policy making process should be communicated and presented to the stakeholders in the beginning of the process.

4.3. Stakeholders for Decisions

One of the arguments to involve stakeholders is that they possess unique knowledge. In policy processes we make a distinction between the use of procedural knowledge, scientific knowledge and local knowledge. Procedural knowledge is knowledge about which laws and regulations are applicable, the procedural stages of these laws or regulations, and the timing of them. Scientific knowledge is the formal knowledge, most of the time encoded in reports or models, that can be used to understand the problem or to find solutions. Local knowledge is tacit knowledge of the people living in the area that resembles specific knowledge about certain aspects of the environment. Stakeholders can bring in all three types of knowledge to the process, but especially the last one can be of great importance to the policy problem. In the process design, therefore, much attention should be paid to create opportunities to bring in knowledge, to articulate the important questions and to produce new knowledge together.

Well-designed collaborative knowledge production processes help to generate meaningful results for the involved policy makers, scientists and stakeholders by joint production of documents, models, etc. People who can combine different fields of knowledge and can attach to different communities play an important role in the processes that guide the activities.

5. Defining Evaluation Criteria

The process path and decision points shown in Figure 5 requires that clear evaluation criteria are defined for each stage of the process. In its early phases, the progression of a solution may be a simple matter of judging performance against a single criterion. In the case of a technical solution, the early stages of the evaluation process would be where the key question "does it work?" would apply.

For example, in the case of assessing the viability of ducted wind turbines for the Glasgow EV charging hub, the decision to progress with PV alone was based on assessment of only energy yield; in the case of ducted wind turbines, this was so low in comparison to PV, that it made the technology infeasible.

If a solution is technically non-feasible, then there is little point in applying other layers of analysis such as financial or social. However, as a design progresses to its latter stages the basic question "does it work?" needs to be more nuanced, becoming "does it work in *this* particular context?" A solution would typically need to be assessed against multiple technical, social and economic criteria as outlined in Section 5.6.

5.1. Overall Goal of a Smart Solution

The overall aim of RUGGEDISED is to boost the adoption of sustainable solutions in cities. So, clearly, key smart solution performance evaluation criteria must be the associated reduction in greenhouse gas emissions, reductions in energy and resource use (NB RUGGEDISED's data platform solutions fall into this category) and boosting the deployment of sustainable energy technologies. However, a sustainable solution needs to fulfil a broader range of criteria other than just those related to energy. To be replicable and successful, any smart solution needs to (eventually) be economically viable and to demonstrate a tangible social benefit in order to achieve buy-in from citizens.

In the case of Umea, smart solutions U1 – U3 were not only evaluated for their technological performance (e.g., energy efficiency improvement or emission reduction); but both a quantitative and qualitative analysis was done in combination with the Business Model Canvas approach, in combination with different business logics (business as usual, joint venture and cooperative).

In RUGGEDISED U1 and U3 the actors involved in the business of energy supply and demand in the city are Umeå Energi AB, Västerbotten County Council and Akademiska Hus AB. To align business models of more than one actor, which steers towards less climate impact, they identified the driving forces for all concerned actors. Driving forces which have been considered are economic but also value based and could be:

A. Profitable for all actors

B. Profitable for one or more actors

C. Other financial gain (indirect benefit) for one or more actors

D. Short term cost but long-term gain for environment, brand name or similar

The Triple Layered Business Model Canvas (as mentioned in RUGGEDISED deliverables D3.2 and D3.3) extends the original business model canvas by adding two layers: an environmental layer based on a lifecycle perspective and a social layer based on a stakeholder perspective. When taken together, the three layers of the business model make more explicit how an organization generates multiple types of value – economic, environmental and social. The integrative approach of the Triple Layered Business Model Canvas (TLBM) allows a more comprehensive view of an organization's environmental and social impacts as well as business model innovation in all three dimensions.

The usage of the social and environmental layers, combined with an economic rationality, seems crucial in those cases where goals of business model innovation imply addressing environmental and societal issues. Therefore, during the implementation stage it is of vital importance to predict and monitor changes that an innovation induces on all three layers.

5.2. Energy Criteria

The majority of the RUGGEDSED smart solutions are energy-related projects; however, their scope is diverse. Examples of technical criteria applied within ruggedized include:

- energy demand reductions from smart building solutions;
- heat recovery from waste and ambient energy streams;
- impact of smart solutions on peak electrical demand;
- utilisation of renewable energy;
- generation of renewable electricity;
- seasonal (heat) storage capacity requirements;
- storage effectiveness (e.g. improvement in performance due to the addition of storage);
- smart transport hubs;
- city-wide data-based decision platforms.

A suite of supporting modelling tools has been deployed (or developed) in RUGGEDISED and used to generate the underpinning performance data in order to gauge performance against energy criteria such as total energy use, reduction in primary energy demand; renewable energy utilisation and reductions in peak demand (particularly peak electrical demand). This data can also be used to derive additional performance metrics as will be outlined later.

As an illustrative example, the general purpose modelling tool MATLAB (mathworks.com) was used to assess the energy benefits arising from the application of smart controls to office buildings (solution U4); controlling heating, lighting and ventilation based on occupancy. The modelling work underpinning the design process compared the application of smart controls to a base case of standard time control; this indicated that substantial energy savings could be achieved in cooling and electrical energy use. Interestingly as the model used reflected the systemic nature of buildings (i.e. the interconnectivity of its energy systems), the energy savings in electricity led to a small increase in heating energy demand (Figure 6), as the reduced electricity use resulted in less heat gains from electrical equipment within the buildings - heat gains that would normally offset some of the heating load. This is discussed in more detail in section 8.2.

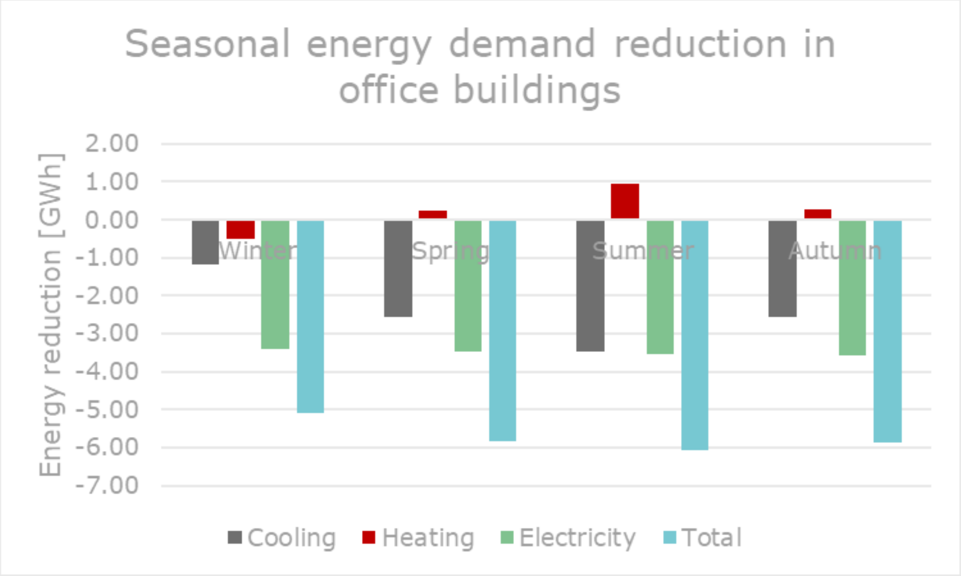


Figure 6: Upscaling of seasonal demand reduction from implementation of smart controls in Umeå office buildings.

5.3. Environmental Criteria

Given that the focus of RUGGEDISED is the sustainability of cities, the reduction in greenhouse gas emissions would be a primary criterion against which to gauge the effectiveness of a smart solution. However, the reduction in emissions is heavily dependent of location and the carbon coefficient of grid electricity.

For example, the EV supported charging hub solution when modelled using the ESP-r simulation (Section 12.1.2) tool for the case of Rotterdam saved approximately 12 MWh of grid electricity per 100m^2 of PV, which equates to 5.5 tonnes of CO_2 savings annually. The same solution applied in Umea saved approximately 9.5MWh of electricity per 100m^2 of PV annually, however this equates to an annual saving of only 114 kg of CO_2; this is due in part to a lower solar yield, but mainly due to the significantly lower carbon content of Swedish (0.012 kg/kWh) electricity compared to that of The Netherlands (0.47 kg/kWh).

Further, whilst the world is rightly focused on the evolving global climate crisis, many cities are faced with a related air quality crisis, caused by the combustion of fossil fuels for heating in buildings, power production and, most pressingly, transportation. Consequently, tertiary environmental metrics for RUGGEDISED smart solutions could include reductions in key air pollutants such as nitrous oxides (NOx), sulphurous oxides (SOx) and combustion-related particulates, particularly PM10s. Energy modelling data can be used as the basis by which to determine reductions in environmental pollutants, provided appropriate data is available, e.g. emissions data per km of travel and the ratio of non-electric to electric vehicles in a city.

5.4. Economic Criteria

Following the logic of the RUGGEDISED Innovation and Implementation framework, what defines a smart city is the connection between smart solutions and the embeddedness of the smart solutions within the existing urban configuration. This means that financial and economic criteria should inherently be looked at, at a broader scale, i.e. on area or system level. Such a scope allows to determine the partners that bear the costs and risks and the partners that gain benefits from a particular optimised energy configuration. The crux is in a fair division of costs and benefits on area level or the level of the energy infrastructure system. Such collaborative business models have been extensively experimented with in Umea. They require, open books, transparency on incentives and interests, and trust. The results show that investments in techniques are optimised on system level, instead of positively impacting individual partners.

5.5. Social Criteria

Economic criteria and sustainable performance play a key role in the assessing the right technical configurations. However, social criteria are crucial due to the fact that they are hard to measure, and are therefore often overlooked. For smart heat grids and isolation solutions, comfort is an important criterion. Moreover, to ensure the uptake of smart user interfaces and urban data platforms, transparency, user-friendliness, privacy etc., determine the success.

As an example, the modelling of load shifting in the Drygate flats in Glasgow focused on the size of battery required to support space heating using electricity from low-cost, off-peak periods. This system would replace a poorly performing thermal storage heating system that performed the same task. In this case the energy and cost savings are small, as the two systems (storage heating and battery supported heating) are performing the same function, however the modelling can also provide information on indoor environmental conditions in the flats in addition to energy performance. This data showed a substantial improvement in comfort conditions compared to those achievable with the existing storage heating. So, whilst from and energy and economic perspective, the benefits are modest, from a social perspective, the indoor conditions for the residents of the flats would by substantially improved, with knock-on benefits to health and wellbeing.

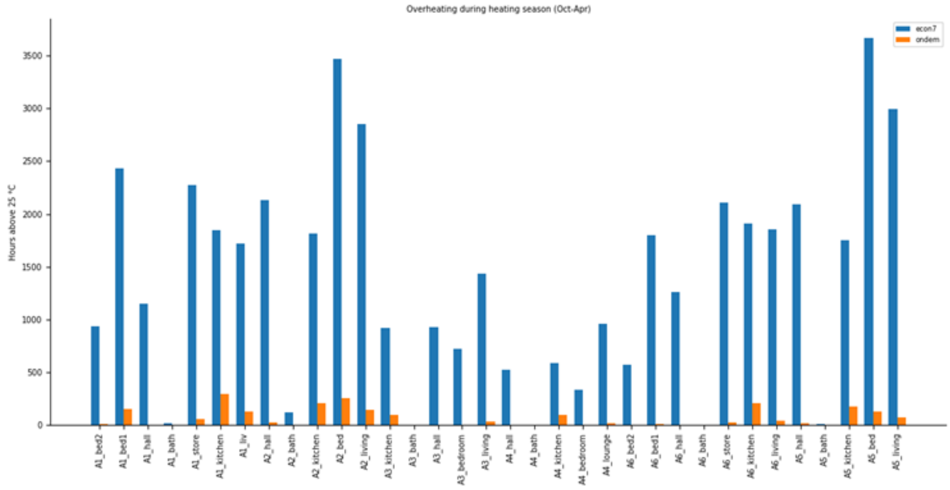


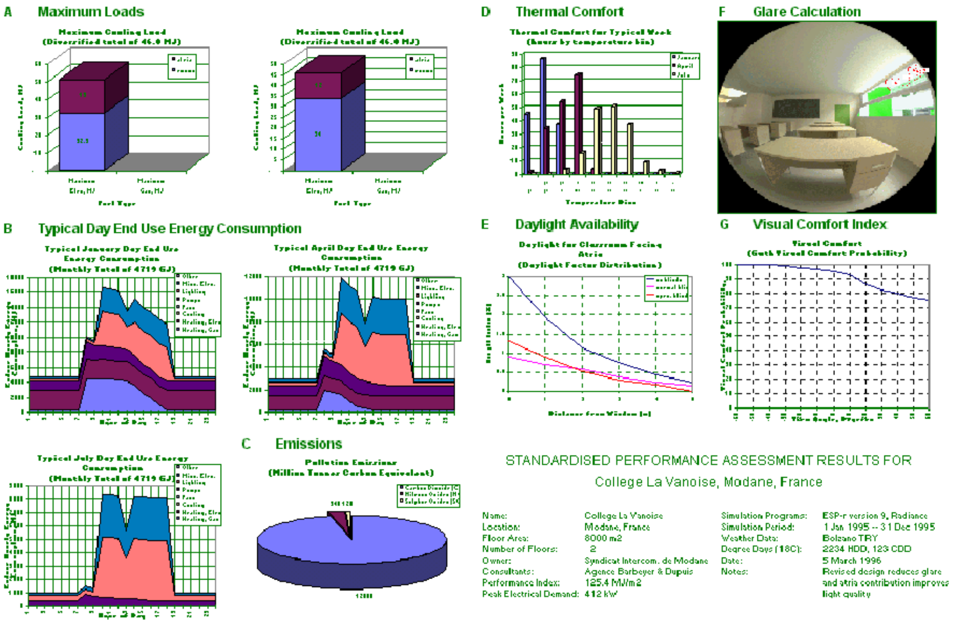
Figure 7: improvement in comfort (reduced overnight heating) in Drygate flats due to changing from overnight storage heater charging to battery supported on-demand heating.

5.6. Multi-objective Evaluation

With the range of criteria outlined above, it becomes more difficult to provide a succinct metric for the performance of a smart solutions, given that the criteria themselves are distinct and heterogeneous. Various approaches are available to help smart solution design teams select between solutions evaluated using a group of disparate metrics.

5.6.1. Integrated Performance View

An approach which is deployed in the building energy modelling community, and which was derived from a previous European project (Daylight Europe [DL-e]) is the *integrated performance view* (IPV), Clarke (1998). This is an approach which attempts to present a range of dissimilar performance information to a design team in a relatively compact format. An example is shown in Figure 8, where power, energy, thermal comfort, emissions and lighting data are displayed on a common display format; this allows the change in performance between different design variants to be assessed.



STANDARDISED PERFORMANCE ASSESSMENT RESULTS FOR
College La Vanoise, Modane, France

Name: College La Vanoise
Location: Modane, France
Floor Area: 8000 m2
Number of Floors: 2
Owner: Syndicat Intercom. de Modane
Consultants: Agence Barbeyer & Dupuis
Performance Index: 125.4 MJ/m2
Peak Electrical Demand: 412 kW
Simulation Programs: ESP-r version 9, Radiance
Simulation Period: 1 Jan 1995 -- 31 Dec 1995
Weather Data: Bolzano TRY
Degree Days (18C): 2234 HDD, 123 CDD
Date: 5 March 1996
Notes: Revised design reduces glare and atria contribution improves light quality

Figure 8: example of an *integrated performance view* for the implementation of demand reduction measures in a schools building.

Whilst the IPV provides a means to view a range of disparate evaluation metrics from one or more modelling tools, and provides the data to help the design team make a decision, it does not in itself provide information on whether performance is good bad or indifferent. The decision on performance would need to be made based on the expertise of the design team and negotiation between them regarding which performance metrics are more or less important with a view to achieving the overall goal of the smart solution.

5.6.2. Weighted Non-dimensional Metrics

The use of weighted metrics builds on the use of modelling to supply data for the design process. A weighting factor can be applied to each assessment, which would turn a value such as annual energy use, into a non-dimensional score. So for example:

$$S_h = E_h \times \omega_h$$

Where E_h is annual heating energy use in kWh and ω_h is the heating energy weighting in kWh^{-1} . When weightings are applied to the range of performance metrics being considered, the results can be summed to provide a total performance score for a particular design option. For example

$$S_T = \sum_{i=1}^{i=n} S_i$$

Where S_T is the total non-dimensional design option score and S_i would be the score for a particular performance metric such as energy, emissions, capital cost, etc.

Whilst this approach delivers a single performance score that integrates all of the performance criteria being considered, the derivation of the different weighting factors introduces a significant degree of subjectivity and (like the evaluation of an IPV) requires negotiation between the range of stakeholders involved in the design decision.

6. Tools

6.1. Tools and the Role of Modelling

The key role of modelling within RUGGEDISED SEDP is to allow the design team to test different design options and provide data, allowing decisions to be made at each decision point of the process shown in Figure 5, enabling the design to move on to the next stage of the process, highlighting the need for the design to be amended or the need to rethink and move back to an earlier stage of the design process. In the latter stages of the design, the model can also be used to provide information on the likely performance of a smart solution in-situ.

6.2. The Modelling Ecology for Urban Smart Energy Systems

There are a wide range of smart solutions under investigation within RUGGEDISED. The evaluation of each of these projects, against the range of criteria outlined previously, requires a multi-tool approach. Consequently, the SEDP being outlined in this report can accommodate a range of modelling tools in order to generate the data required to inform the design team and to evolve a smart solution.

An example of a multi-tool approach is shown in Figure 9, which shows the range of tools being applied to the various systems being deployed on the Glasgow smart street. The portfolio of tools includes some specifically developed for RUGGEDISED.

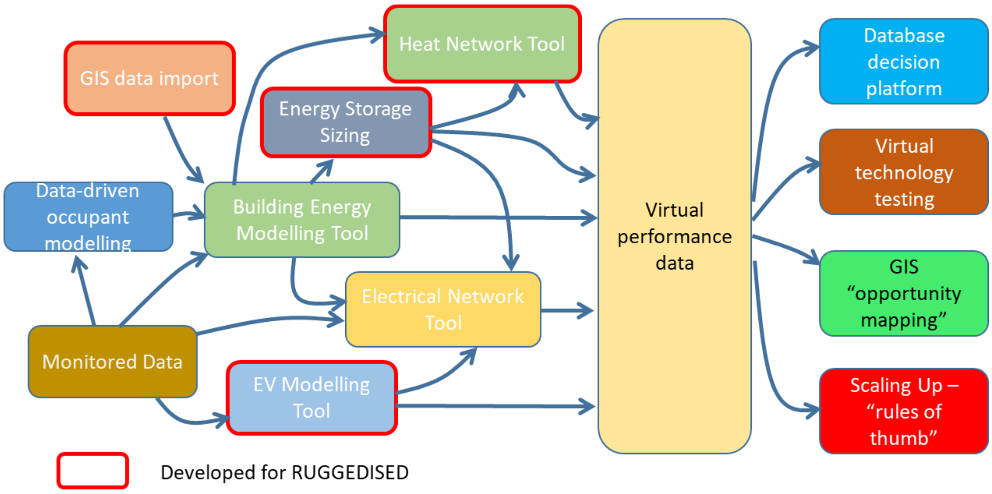


Figure 9: Modelling 'ecology' for the Glasgow smart street.

The tools are predominantly used to assess the technical performance of the Glasgow smart solutions – generating virtual performance. However, the same data can also be fed into other types of analysis such as a financial assessment of performance or a risk analysis.

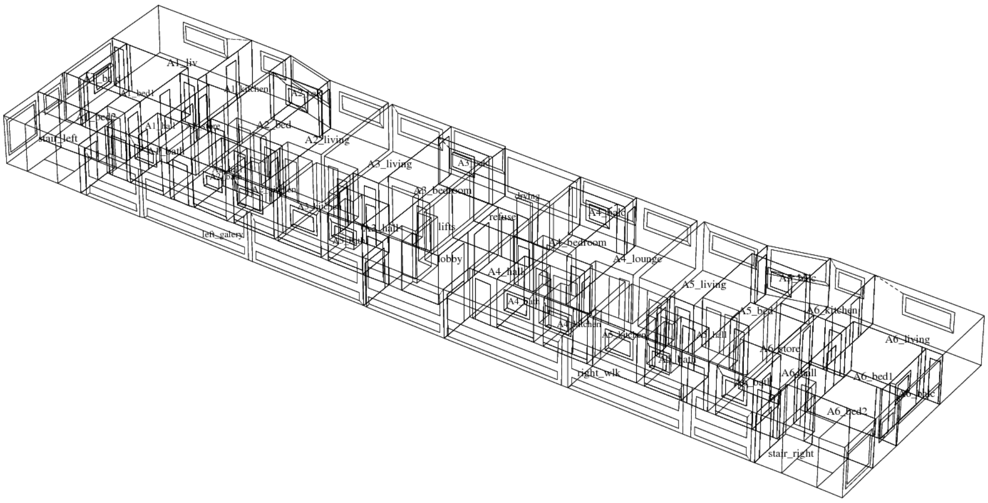


Figure 10 shows the model of the Drygate high-rise flats on the Glasgow smart street, which was used in a study focused on battery-supported load shifting. The flats are currently electrically heated using a crude load load-shifting technology, known as storage heating. This uses thermally massive heaters to absorb electrical energy overnight during periods of low electricity costs. The stored heat is then discharged into the dwelling during the day. However, the thermal performance of storage heating is often poor due to a range of factors including the use of poorly understood manual controls; inflexibility in charging times; and heat leakage due to poor insulation of the thermal mass. This often results in poor thermal comfort for occupants.

The aim of this activity was to investigate the size of battery needed to allow the storage heaters to charge closer to the time of use. Typically, the need for heat occurs during periods of high electricity demand (morning and evening) and hence high cost. In the proposed solution, the battery would charge during low-cost electricity periods and then support the electrical heaters in the flats, allowing them to charge closer to the time-of-use. The advantages of this approach are reduced thermal energy losses: heat is stored in poorly insulated storage heaters for a shorter period of time; reduced heating costs and improved thermal comfort for occupants.

This modelling study required the use various tools.

1. The primary tool used was ESP-r, which was used to model the thermal performance of the flats under different heating regimes (e.g. the current regime and battery supported operation). The model of the Flats is shown in Figure 10.
2. An occupant modelling tool (Flett & Kelly, 2017), which uses socio-economic input data, was used to generate high resolution occupancy data including times of active occupancy, small power loads and hot water usage, which is suitable for use in a building simulation tool analysis.
3. The battery size required for load shifting was calculated using another tool specifically developed for the project, which scans demand profiles (and supply profiles, if applicable) to determine the battery capacity required to support electrical heating.

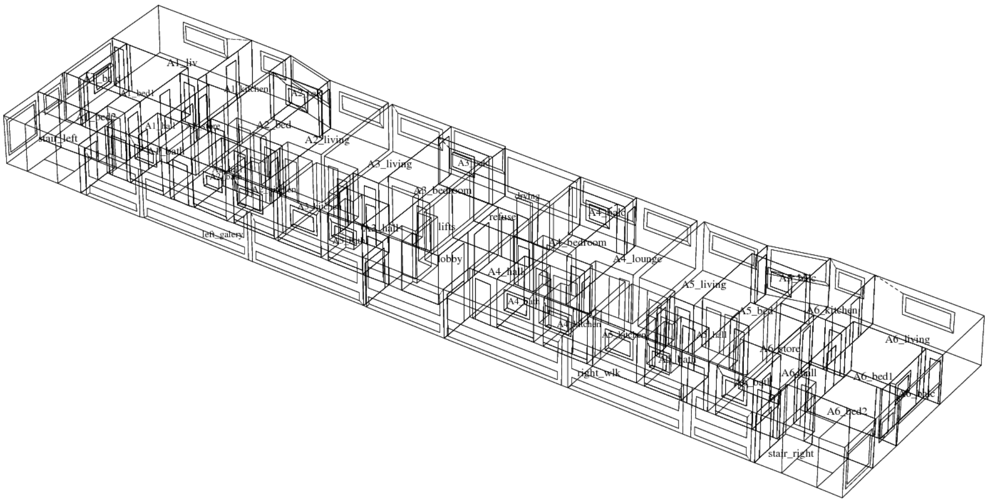
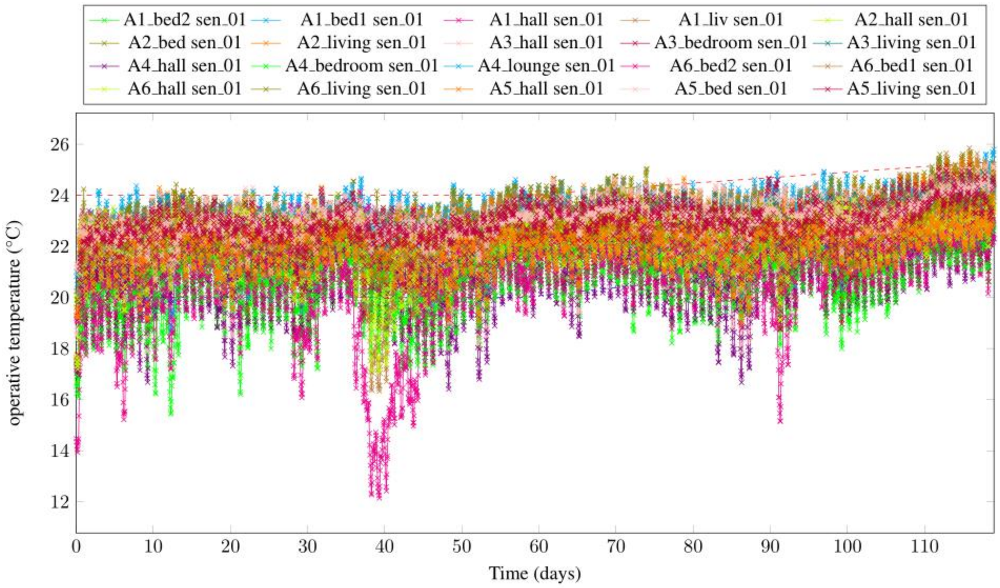


Figure 10: ESP-r model of a floor of the Drygate Flats.

An example of simulated temperatures from the technical analyses are shown in **Error! Reference source not found.**.



The data from the modelling exercise indicated that using batter-supported heating in the flats, where heat was supplied closer to the time-of-demand, resulted in energy savings of around 20% and significant improvements in thermal comfort (Allison *et al*, 2019). The battery capacity required to support load shifting was approximately 10 Wh per kWh of annual heat demand.

6.3. Identifying Strategic Opportunities

6.3.1. Opportunity Mapping

The example illustrated previously and in Section 8, are examples of how technical modelling can inform a design process. However, technical modelling is only one aspect of the range of decision support tools available for smart energy projects. Whilst not used directly for the illustrated cases, geographical information systems (GIS) can play a role both in strategically identifying clean energy solutions of cities and as a repository for both real and simulated information on the performance of energy systems (see Section 7.1.3).

For example, in addition to identifying car park rooftops for the location of photovoltaics (PV), Glasgow City Council and the University of Strathclyde undertook a separate study looking at the applicability of siting PV on vacant derelict land (VDL) within the city.

Two different sets of constraints were to be considered for appraisal of potential sites. Technical factors imposed by the location on the economically achievable power level; and planning and environmental policies affecting the likelihood of receiving planning permission for a technically feasible scheme. Locations in the city may be affected by several individual technical and policy factors, so a realistic combined view of the constraints required weighting and combining factors to give an overall technical and policy score.

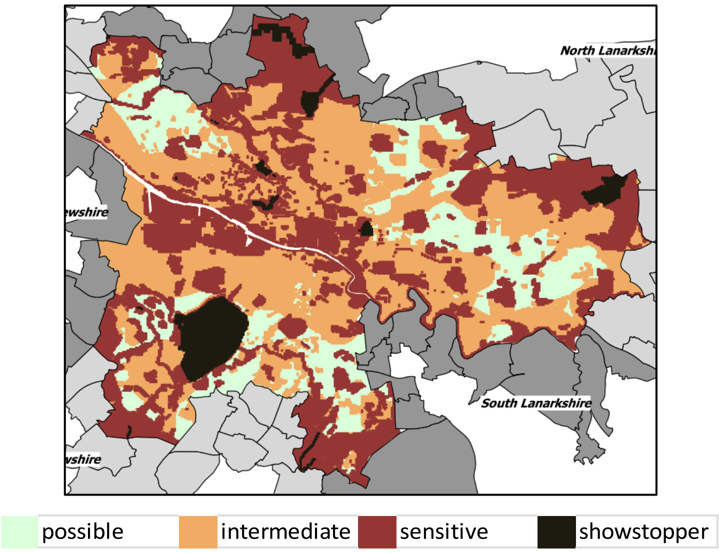
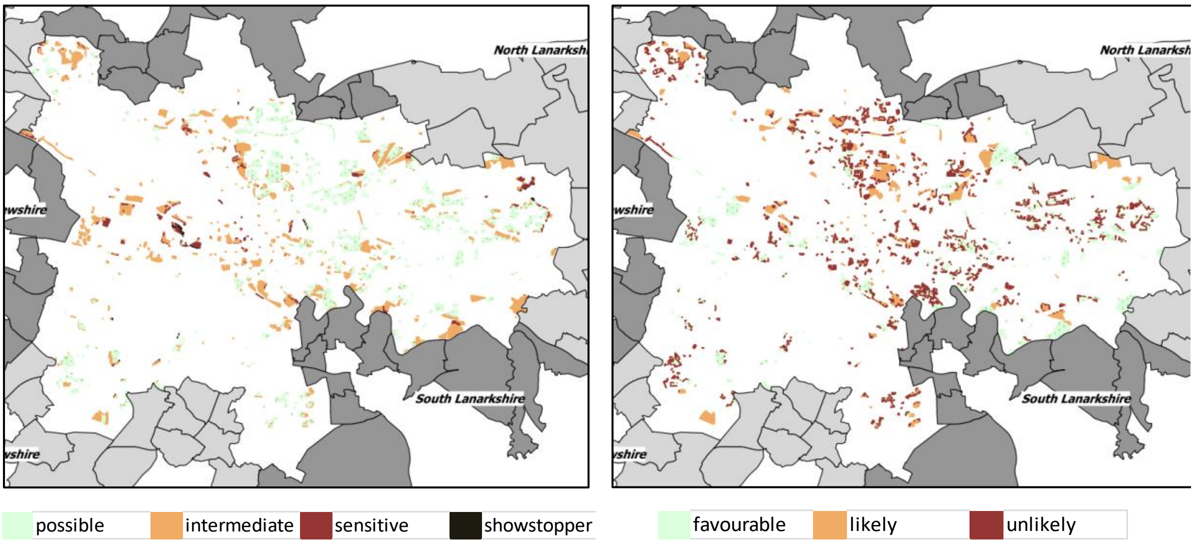


Figure 11: GIS mapping showing where PV installations are very possible (green) to not possible (black).

Technical factors are technology specific. Four factors were identified as affecting freestanding solar PV: the connection distance to an electricity substation; the degree of congestion around the substation; the degree of overshadowing from surrounding buildings; and terrain access problems or flooding risk. Scoring criteria to rate these as favourable, likely or unlikely, and weightings to give a combined technical score, involved the input of the distribution network operator Scottish Power Energy Networks (SPEN). Policy factors are the same for all renewable technologies but will vary by Local Authority. Five were identified for Glasgow: environmental designation (such as Site of Special Scientific Interest or Listed Building); development zoning (such as industrial or housing); glare that might constitute a safety risk; possible existence of endangered species; and visual impact on neighbouring housing. Scoring criteria to assess each of these as possible, intermediate or sensitive and weightings to give a combined policy score was developed in jointly by Glasgow City Council and the University.

The constraints were developed as layers on a GIS tool, which was then used to visualise how individual and combined scores varied spatially across the whole city, allowing the user to look not just at overall suitability of a site but also to drill into detail about the specific issues that apply so that management or mitigation possibilities could be assessed. Each individual factor and combined score were displayed in a layer (shape file) on a 50 x 50 m grid across the city. For some factors, data existed for the whole city, while others required a detailed survey of individual sites. A three-stage process was developed for the evaluation of PV potential: citywide scoring; mapping these onto the VDL sites; and finally, a combined scoring for the surveyed VDL sites only.

Different combination methods were applied, which gave rise to different perceptions about the size of the opportunity available. The stringent method - which applied the worst score for any individual layer as the combined score – showed around 16% of the VDL area as technically favourable, while the lenient method - which added up individual factor scores - showed 43%. Similarly, stringent combination of policy scores showed 8% as possible, while the lenient method showed 47%. Planners can select the most appropriate combination method depending on whether they wish to encourage maximum deployment of renewables or to minimise the technology impact.



Policy

Technical

Figure 12: GIS mapping showing where PV could be installed on VDL in Glasgow for policy and technical constraints respectively.

6.4. Evaluating Concepts & Providing Data for Decisions

This section looks at the types of modelling tools that can be applied in the evaluation of smart solutions within a design process. A catalogue of tools deployed within RUGGEDISED is provided in Section 12.

6.4.1. Building Energy Modelling and Evaluation

Since its appearance in the early 1970s, building energy modelling (BEM) has been used widely, firstly by researchers and later by building design professionals in the assessment of building energy performance. BEM can be used to model the performance of existing buildings, the impact on energy performance of changes to existing buildings, or the performance of proposed buildings.

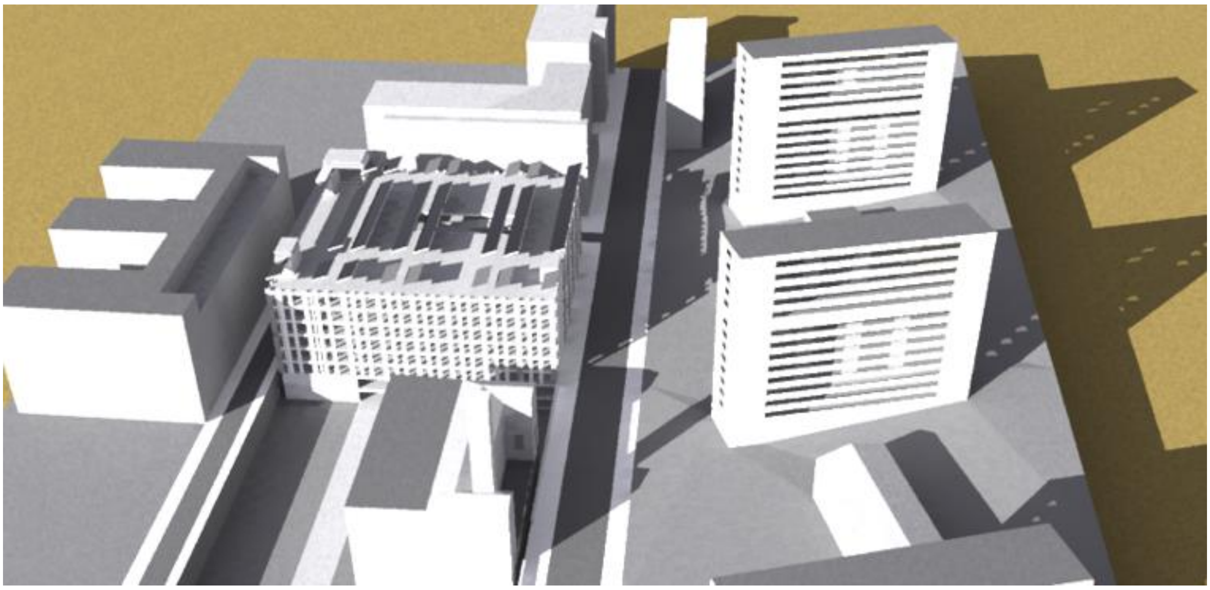


Figure 13: Duke St. geometric model, including the building energy models of the charging hub and the Drygate flats (rendered in RADIANCE).

BEM is typically based around the concept of energy and mass balances; typically, the building can be subdivided into a large number of control volumes that (for example) could represent a layer of material in a surface, the volume of air within a room or a piece of equipment in an HVAC system. A mass and energy balance can then be applied to each control volume and a number of characteristic equations extracted. For a building this could run into thousands of separate equations. Solution of these equations using climate data, occupancy information and user-defined control settings yields the time-varying temperatures, heat fluxes and fluid flows occurring within the buildings: effectively providing a picture of the variation in building energy performance within a defined time frame (a day, week, year, etc.).

Given the level of detail typically found in a BEM, developing one requires a substantial amount of information, including the building geometry, the materials used in its construction, the occupancy of the building and occupancy related heat gains and loads. This is outlined in Section 7.

Originally, building simulation focused on thermal performance and energy use, however, its remit has expanded massively over recent years such that it is regularly used the analyses of building integrated renewable systems, demand side management, load shifting, low-carbon heating and cooling systems, thermal energy networks and electrical energy networks.

Building energy models were used to evaluate energy saving from smart office installations (Umeå); the performance of the Glasgow EV charging hub and thermal load shifting in the Glasgow flats. Modelling of Energy Networks

6.4.2. Energy Network Modelling

There is a range of approaches being deployed within RUGGEDISED to the modelling of energy networks.

Thermal Networks

The prospective Glasgow heat network has been modelled using a variant of the ESP-r building simulation tool. This uses a node and arc scheme to generate a representation of the network, which can then be simulated.

- nodes are points where different elements of the pipework link together or where heat is supplied to or extracted from the network.
- arcs are the connecting components (in this case pipes).

Both nodes and arcs are subject to an energy and mass balance. At the nodes the flow must summate to zero. Additionally, the heat losses (through flow away from the node) must balance any heat gains from heat sources or flow into the node. For arcs, the exit temperature of the fluid is dictated by losses from the pipe to the surrounding ground.

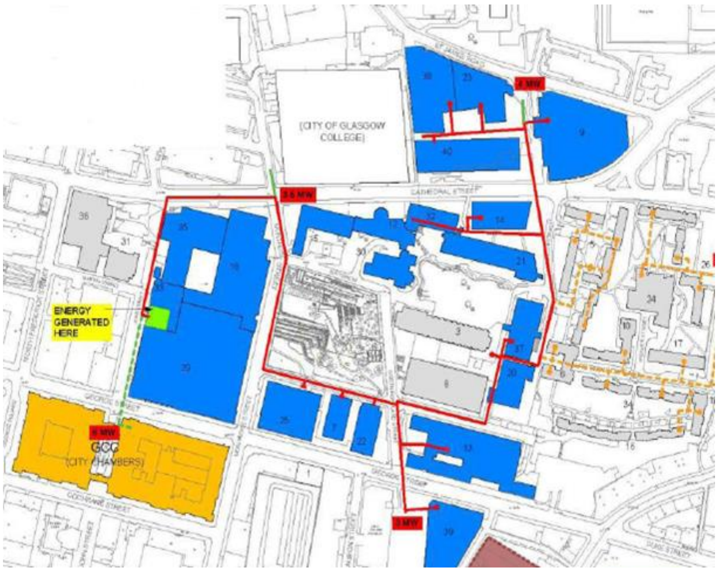


Figure 14: University of Strathclyde district heat network.

Heat losses from the pipe are calculated using an explicit heat exchange calculation, where the heat transfer from the pipe to the surrounding soil is a function of the fluid temperature and velocity, pipe material, insulation thickness and surrounding ground temperature.

Additionally, the pressure around the network is calculated, with pressure drops due to pipe runs and fittings calculated as a function of the supply flow rate. The pressure drop data is also used to calculate the energy demand for hot water pumping. Flows around the network are calculated from non-linear functions of the pressure difference between connected points in the system.

The node and arc network model can be simulated using heat demand profiles as boundary conditions (typically calculated from a building simulation or from measured data) along with information on ground temperatures at the depth of the district heating piping. The simulation results can provide information on pumping demand, heat losses, supply and return temperatures and system efficiency.

Power Networks

Power networks can be modelled using a very similar approach to heat networks, where the network is also modelled using a node and arc scheme. However, in this case nodes represent points where power is injected into or extracted from the network or junctions between system components or linkage points to other (larger) electricity networks.

The building simulation tool ESP-r also includes a power network modelling algorithm. In this, the solution of the network is based on a power balance at each node, where the summation of real and reactive power is zero and power flows between connected nodes are a non-lines function of voltage difference and connecting component impedance characteristics.

Boundary conditions for the solution of the network can again be provided using measured data or from simulated electrical demand and supply (e.g. from photovoltaics or combined heat and power units). More detail on the modelling approach is provided by Kelly (1998).

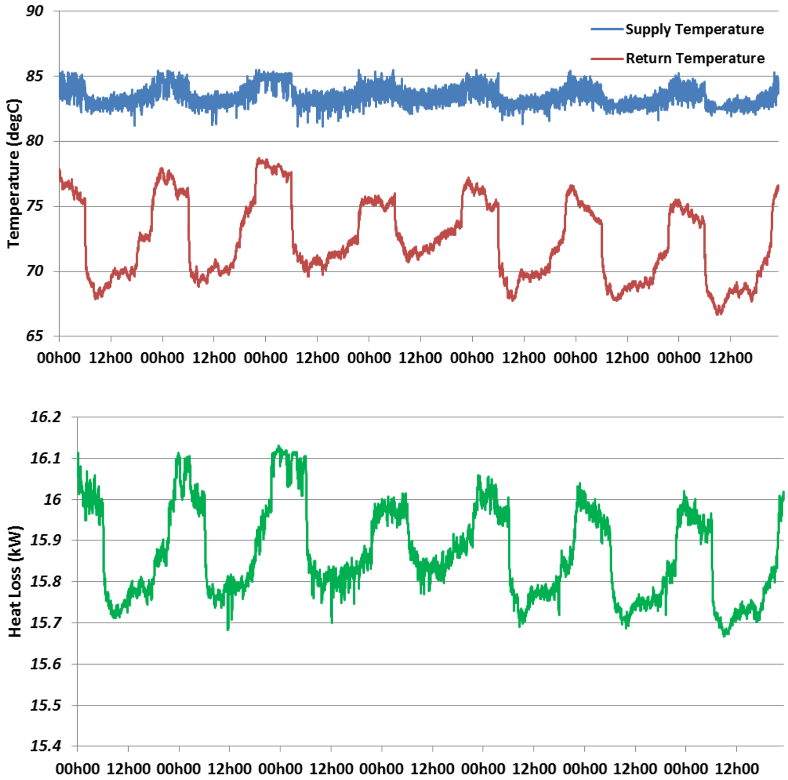


Figure 15: simulated variation in supply and return temperatures and heat loss over a simulated week for the Strathclyde district heat system.

6.4.3. Wider Impact (Scaling Up)

A large part of the modelling effort in RUGGEDISED is dedicated to producing data that can be used to assess the impact of scaling-up the solutions. This requires that modelled results for a specific solution are normalised (typically to an easily measurable parameter), so that the results can be scaled for the other cities. For example, the Umeå, smart office solution results were scaled to per m^2 of floor area; this allowed the benefits for Glasgow and Rotterdam to be determined once a simulation had been undertaken for a “typical” office building in each city using a representative climate. The results were scaled based on an estimated floor area in each city of the office space that the Umeå solution (U4) could be applied to (Section 8.2). Similarly, the Glasgow PV-supported EV charging hub (G5) solution was scaled to the number of vehicle charges per 100m^2 of PV and then the simulated results for the lighthouse cities, scaled to the estimated area of PV that could be deployed on car parks in each (Section 8.1).

6.5. Verification, Calibration

Whilst modelling can provide a useful insight into the likely performance of a design, it is important that the city design team can have confidence in the predictions of a modelling tool. This section discusses verification of the models used in RUGGEDISED. There is a variety of verification approaches that could be applied including comparison to empirical data, comparison to other tools and comparison to simple manual calculations; however, the limits of verification, particularly with regards to the novel or complex systems deployed the lighthouse cities are also discussed.

The building simulation tool ESP-r has been used extensively in modelling Glasgow energy solutions and subsequent upscaling of results to other cities. The tool has been in continual development since the early 1980s and has therefore been subjected to extensive verification with regards to its ability to predict the likely energy and environmental performance of real buildings. Many of these verification efforts are documented by Strachan et al (2008).

Additionally, the PV model used to calculate the power yield from car-park-based PV canopies has been verified against real data and has also been tested extensively in modelling full scale PV installations (e.g. Clarke 1996, 1997; Strachan 1997); the model uses published test data from manufacturers.

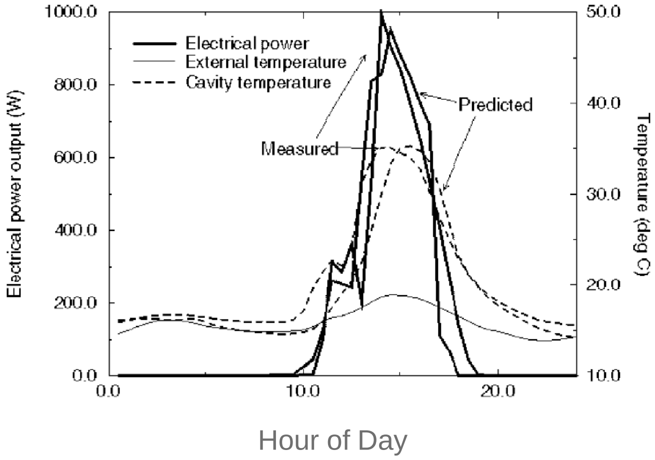


Figure 16: simulated and measured PV output for ESP-r's PV model (Strachan, 1997).

6.5.1. Calibration

The electric vehicle charging tool was developed using empirical data from RUGGEDISED partner Transport Scotland; this consisted of logged charging events at public charge points across Scotland since 2015. The core of the tool is a set of charging probability curves (weekdays and weekends), which describe the probability of a charge occurring at a particular time during the day and the quantity of charge taken during charge events. These are used to predict whether or not a vehicle will charge on a particular day; if charging occurs the model predicts when the charge is taken and the quantity of charge taken and (based on the capacity of the charger) the duration of the charge event.

The calibrated time-of-charging curve used in the model is shown in Figure 17.

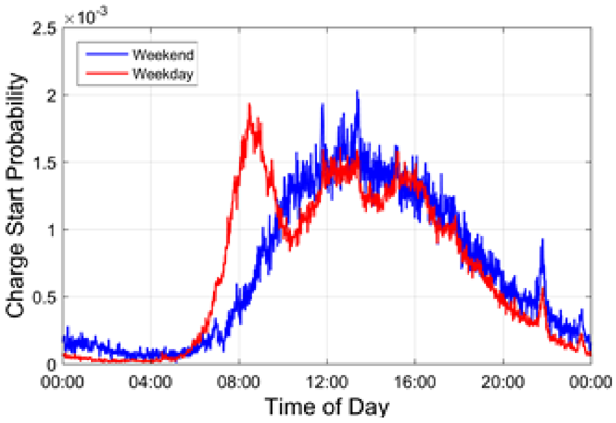


Figure 17: calibrated time-of-charging probability curves used on EV charge tool.

6.5.2. Limits of Verification

There are limits to the verification that can be undertaken in projects such as RUGGEDISED. This applies particularly to novel or complex systems, where performance information may be very limited or non-existent. For example, all of the building simulation models used in RUGGEDISED have been calibrated, however the calibration looks at their ability to calculate performance using quality assured data. The building models used in the cases of Glasgow, Umeå and Rotterdam all use data (e.g. geometry, materials, occupancy) from sources such as surveys or architect's drawings. The output of the simulation is dependent on the veracity of this input data and, as it is not necessarily representative of what actually exists in the actual building, the simulated data can only ever be indicative of what the energy performance of the system being modelled is rather than an accurate representation. The resulting uncertainty in modelled results is discussed in Section 7.1.2.

7. Data

7.1. Data For *and* From Modelling

As was described in Section **Error! Reference source not found.**, modelling tools provide much of the data required on which to make an informed design decision on a smart solution. However, modelling can also provide data to a range of other modelling applications or downstream design decisions. Here, both the sources of information are discussed along with the potential destinations for data.

7.1.1. Data Requirement and Sources of Information

A broad variety of modelling tools have been deployed in RUGGEDISED which requires a similarly broad range of data inputs as indicated in Table 1.

Table 1: typical data requirements for RUGGEDISED modelling tasks.

Modelling task	Data requirements
Buildings	geometrical information; construction information; materials thermal properties; occupancy information; small power loads; equipment heat gains; detailed local climate data; control settings; heat source characteristics.
Heat networks	piping topology; piping materials (inc. insulation); soil thermal characteristics; soil seasonal temperatures; pump characteristics; equipment pressure loss characteristics; flow rates and temperatures; heat load profiles; heat source characteristics; thermal store characteristics.
Electrical networks	electrical network topology; cable/overhead line characteristics; transformer characteristics; grid connection data; real and reactive power demand profiles; generator characteristics or power input profiles; network voltage characteristics.
Photovoltaic (PV) Arrays	PV panel test characteristics; information on array configuration; panel orientation and inclination; weather data for local site; surrounding shading sources; inverter performance data; presence of power point tracking.
EV charging	vehicle numbers and type; vehicle time-of-charge statistics; charge taken statistics; number of chargers; charger capacity; charging points; vehicle-charge point compatibility.

Much of the modelling work in RUGGEDISED centres on the modelling of buildings or urban areas. A variety of data sources have been accessed and these are summarised below.

Pre-existing Databases

A lot of modelling tools make extensive use of pre-compiled data bases, to reduce the data input burden for modelling. There is a wider range of freely-available climate data available for a wide variety of locations around the world. All of the building modelling exercises in RUGGEDISED used existing historical climate data for Glasgow, Umea and Rotterdam. Building simulation tools typically rely on a database of basic material properties such as thermal conductivity, density and specific heat; these are typically usually derived from laboratory measurements.

Building plans

Building simulation tools are typically reliant on building plans to source information on the geometry and construction. Usually this requires manually translating a 2-D drawing to a 3-D or quasi 3-D building simulation model. It is also possible to automatically import data from a CAD drawing or BIM model; however, there is a significant difference between the geometrical semantics used in building simulation and those employed in CAD (e.g. in CAD there is no notion of a thermal 'zone': one of the underpinning structures of building simulation, consequently, automated translation and re-use of data is difficult.

Building plans are also used to source information on building constructions – i.e. the materials which comprise the different elements of the building fabric. As with geometry, this would normally be input manually into the building simulation model.

For example, building plans were used to derive the data for the models of Glasgow high rise blocks and also for the charging hub.

Manufacturer's Data

Manufacturer's data has been used in the modelling of the Glasgow charging hub (G5): both for the properties of the photovoltaic materials and also for the battery operating characteristics. This data was used as input to the respective models.

Metered Data

Extensive data on EV charge point use in Scotland was used to calibrate the statistical model behind the EV charge profile tool (Section 12.1.4). This was used to generate demand profiles for different numbers of electric vehicles. Additionally, measured electrical demand data was used as an input boundary condition when undertaking the EV-PV-charging hub performance simulations.

GIS and Map Data

Geographical data has been used in several of the modelling exercises. For example, when constructing models of the piping systems in the Rotterdam and Glasgow, pipe routing diagrams and maps were used to determine run lengths and depths. Further, in the modelling of the Glasgow PV-EV charging hub, GIS building shape data was used to develop models of surrounding (overshadowing) buildings.

Survey Data

Data from the UK Time-use-survey was used to calibrate the statistical models underpinning the household profile tool (Section 12.1.5). This was used to generate the diverse range of occupancy, hot water demand and small power demand used in the simulation of the Glasgow high-rise load shifting solution (G8).

Technical Standards

Many of the assumptions underpinning the notional Umea office model used to estimate the possible energy savings from smart energy solutions were derived from technical standards (Sveby, 2013).

7.1.2. Data Uncertainty

The verification of modelling tools to test their ability to predict technical performance typically uses well characterised datasets on well-defined problems; the ultimate aim of the exercise is to assess the ability of the algorithms underpinning these modelling tools to accurately predict performance through comparison to experimental or analytical data. However, when modelling real systems: buildings, energy networks, etc. The modeller is reliant on a variety of data sources (many of which are outlined previously), which may be of variable quality and which may or may not reflect the actual system being modelled. Some illustrative examples are as follows.

- Modelling of systems, whose behaviour is governed by variations in climate, such as renewable systems or buildings, typically use historical data such as test reference years. However, this data may not reflect climate conditions in the immediate locality being modelled (the microclimate), nor may the data be reflective of ongoing changes in climate due to climate change (i.e. more extreme conditions).
- Tools such as building simulation tools rely on databases of measured performance properties of materials to reduce the data input burden on users. However, the properties of same materials used in actual buildings being modelled may not be the same for a range of reasons: the performance of materials may degrade over time though moisture ingress, the characteristics of the material used in the building could be different from that tested the lab to generate the database information.
- Further, data from plans and maps may not be representative of what actually exists in-situ: materials listed in plans may not be the same as those actually used in the building construction; pipes and cables shown on city plans may take a different route from those indicated.
- Using standards data when populating models with input information can be problematic in that the standards may not reflect what happens in the actual situation. For example, using standard occupancy patterns (e.g. as used in the modelling of the Umeå smart office) when simulating the performance of a building model may not be reflective of the occupancy occurring in the real building.
- Finally, the majority of modelling tools simulate an idealised version of reality, in most cases equipment and systems are assumed to work properly and the impact of defects and faults are rarely considered, despite the fact that in most complex systems such as buildings and energy networks, defects are inevitable.

The examples above highlight that there is significant uncertainty when modelling real system in terms of the veracity of the data used to populate the model and also in whether or not the model provides a realistic representation of the actual system. All of this contributes to significant uncertainty in the output of models, such that numerical predictions of performance should be treated with caution. There is a growing body of evidence that modelling provides an over optimistic view of performance: often termed the ‘performance gap’, (e.g. De Wilde, 2014) between actual measured performance and what emerges from simulation.

One means of accounting for the performance gap and data uncertainty is to run multiple simulations, perturbing the one or more of the input data within uncertainty bands, thus providing a range of simulated results rather than a single value for a performance parameter such as energy consumption (e.g. Macdonald and Strachan, 2003) and accounts for likely uncertainty. The problem with this approach is that a) it is computationally and time intensive and is rarely done within a time-constrained design process and b) the uncertainty associated with input parameters to models often is not well known.

Consequently, modelled results presented in RUGGEDISED should be regarded as providing and approximate rather than accurate indication of likely real-world performance. However, absolute values of energy use, temperature, etc. There is therefore, some risk that incorrect design decisions may be made based on inaccurate simulation results. However, the insight provided by modelling how a system is likely to perform would vastly outweigh the risk of proceeding down a design path without any modelled performance feedback.

7.1.3. Data Destinations: GIS, DDSP

As was described in Section **Error! Reference source not found.**, modelling tools provide much of the data required on which to make an informed design decision on a smart solution. However, modelling can also provide data to a range of other applications.

Modelled technical performance data can be used to populate geographical information system layers (GIS). For example the urban PV mapping exercise described in Section 6.3.1 used simulated performance data on energy yield (provided by ESP-r) and information on possible overshadowing of PV sites (provided by RADIANCE).

Another example Figure 18 shows data from the EV charging tool, which was specifically developed for RUGGEDISED, that has been imported into the QGIS tool; this shows a visualisation of charging point occupancy at the Duke St charging hub.

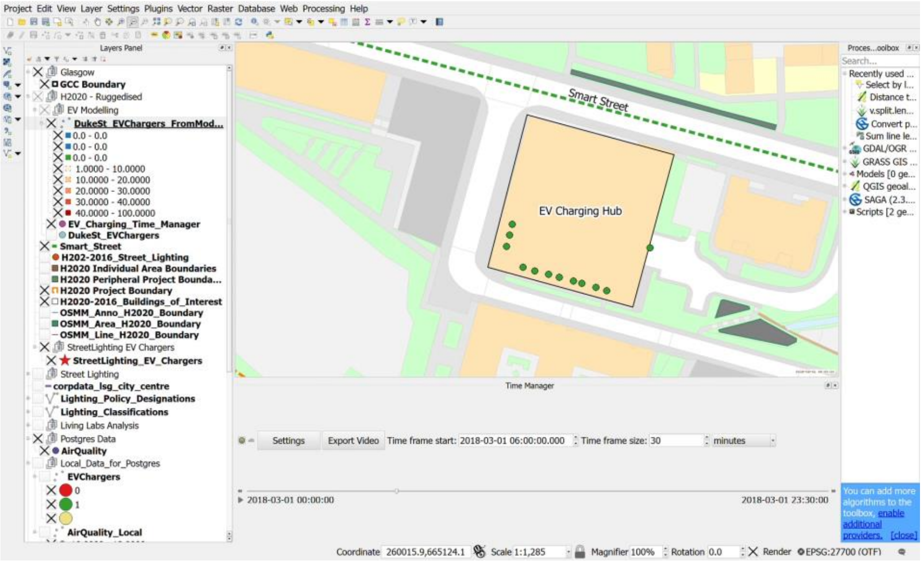


Figure 18: charging hub occupancy predictions shown in Glasgow decision support platform.

As part of RUGGEDISED, the city of Glasgow is developing a data-driven decision-support platform that can also be a destination for data from modelling tools (DDSP). This is a vendor-agnostic platform capable of supporting data in a range of input formats and from a range of sources. Developed with future support in mind, the platform incorporates the ESRI Javascript API Software Development Kit (SDK), which allows data from the Corporate GIS platform to be consumed and overlaid with other datasets. The platform supports the direct referencing of APIs – internal and external to GCC – allowing real-time data to be overlaid onto static corporate datasets. Synthetic data (from modelling) can also be consumed by the platform.

A range of analytical tools are supported in the platform – maps, charts, etc – all of which can be saved as ‘widgets’ and saved to thematic dashboards. An example dashboard is shown in Figure 19 below. These dashboards can be saved and shared across the council and beyond. Each time a dashboard is accessed or refreshed, the latest data will be presented to the user.

Finally, the platform has been designed with non-data professionals in mind and, as such, has an intuitive, user-centric look-and-feel, which allow users to analyse datasets with minimal training.

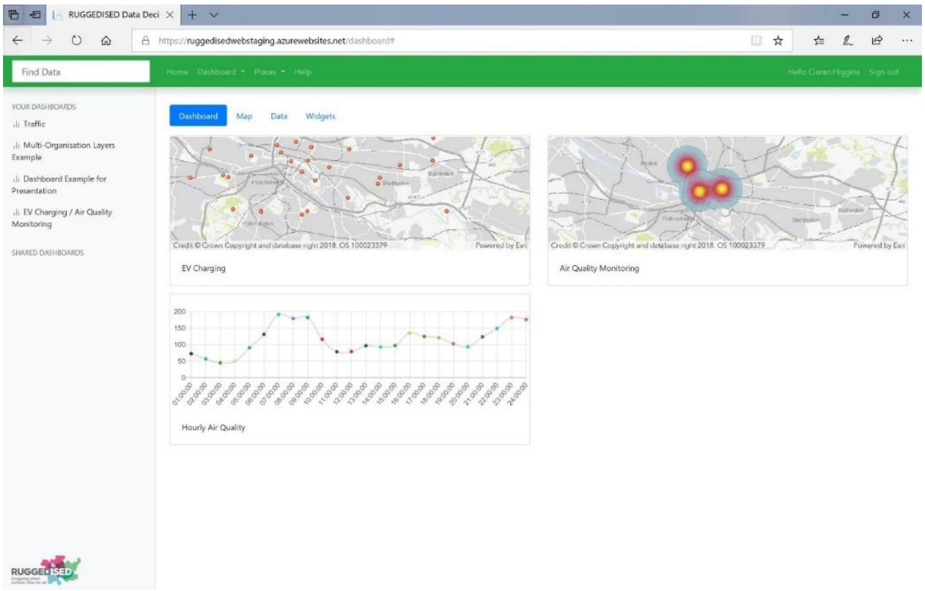


Figure 19: the Glasgow data driven decision support platform (DDSP).

In the cases illustrated, a wide range of performance data can be sourced from detailed modelling tools and then visualised using more generic information dissemination platforms. This allows the key messages contained specialist data to be disseminated well beyond an immediate project design team. Also as indicated later these tools could also be used to highlight discrepancies between modelled and real data.

8. Illustrative Studies[4]

There are a wide range of smart solution projects within RUGGEDISED, all of which have applied modelling in the development of the smart solution to a greater of lesser extent. The following examples show how the models have been applied for decision support, and how this relates to the smart energy district planning SEDP framework set out in Section **Error! Reference source not found.**.

8.1. Urban Photovoltaics for EV charging

One of the Glasgow projects, which included several smart solutions, was an electric vehicle (EV) charging hub on Duke Street, close to the centre of the city. The ambition was that charging would be supported by a roof mounted photovoltaic (PV) canopy, ducted wind turbines and interactive battery storage (integrating elements of smart solutions G2, G4 & G5).

This section summarises a comprehensive design modelling exercise, described in more detail in Allison and Kelly, 2018, describing how modelling was used to support design decisions.

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[4] These summaries were taken from detailed reports provided by the partners. Some of this information also features in the scale up of solutions reported in WP 6 (deliverable 6-4).

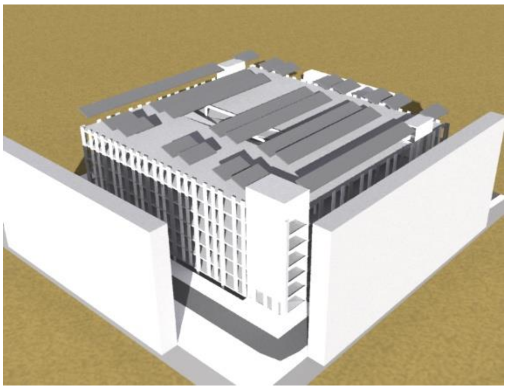


Figure 20: Duke St. car park BEM.

The design questions addressed through modelling support were as follows. What was the likely energy yield from wind and solar energy? What was the best size of battery to support vehicle charging? What was the impact of scaling-up the solution city-wide?

8.1.1. Energy Yield from Renewables

The initial design for the EV charging hub included both a photovoltaic canopy and roof-mounted ducted wind turbines. Modelling was required to assess the likely energy yield from these technologies. This involved the creation of a car park building model, equipped with both a PV canopy and ducted wind turbines. The simulation was undertaken on the ESP-r software (see 12.1.2); the model of the car park is shown in Figure 20: Duke St. car park BEM.

The criteria used to assess performance was the annual energy yield (kWh/m^2) from each renewable technology. The area of PV that could be deployed was known at the beginning of the modelling exercise (1250 m^2), as was the point on the car park where a (ducted) wind turbine could be installed. The turbines size investigated had a swept area of 3m^2. The energy yield from each technology was determined by simulating the performance of the car part over a calendar year using a Glasgow climate data set.

It became evident from the modelling results that there would be an extremely small amount of energy produced by the ducted wind turbine in comparison to the PV array (Figure 21 and Figure 22). Consequently, the Glasgow City Council team took the decision to proceed with a PV-only energy systems design.

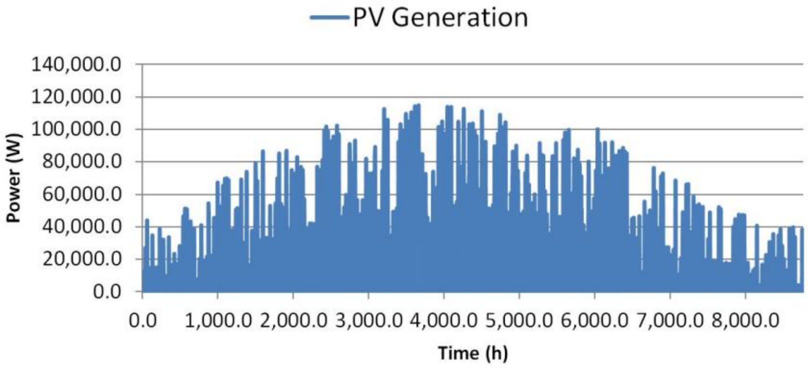


Figure 21: predicted PV generation from car park.

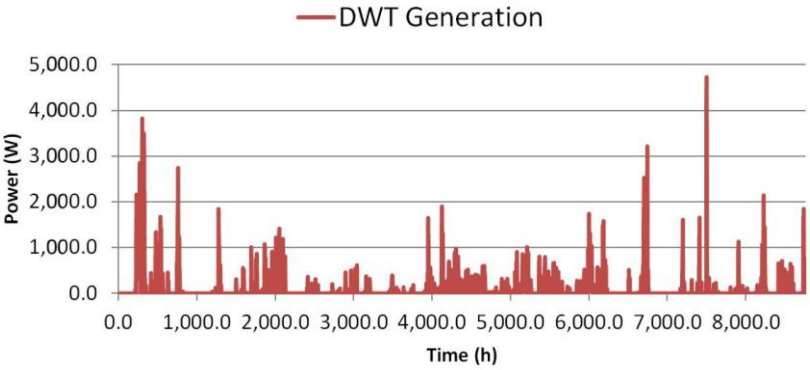


Figure 22: predicted wind turbine generation from car park.

With reference to Figure 5, the process described is as outlined below, where the simulated performance of two technologies was evaluated based on a single criteria and a decision made by the GCC team (with input from the modelling team) to proceed with only a single renewable energy source.

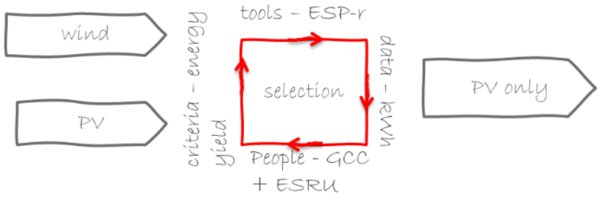


Figure 23: model-based technology selection.

8.1.2. PV Supported Charging System Design

Modelling was used again in the next design stage of the car park design to help identify an appropriate battery size for the car park charging facility. This was not straightforward, as the number of EVs that the facility was likely to serve was unknown. Consequently, a custom-built EV charging tool (Section 12.1.4) was created by the University of Strathclyde, using data from project partner Transport Scotland. This allowed the electrical demand of any number of electric vehicles to be calculated, based on a probabilistic model, which determined whether a vehicle would charge in a user-defined time frame and the quantity of charge taken. The tool was used to calculate electrical demand profiles for different populations of EVs that could potentially use the charging hub. An example of the tool output is shown in Figure 24 shows typical output from the model.

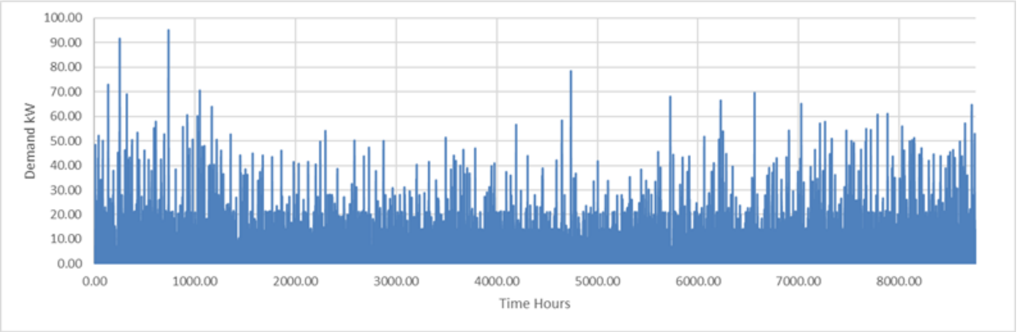


Figure 24: simulated vehicle charging load from the EV charge tool.

With knowledge of a) the existing car park electrical loads and b) using the simulated PV generation and c) the simulated vehicle load, the import and export of electricity between the car park and the electricity network could be calculated. The same data could also be used to determine the size of battery required to support PV charging. Typical modelling output is shown in the Figure below.

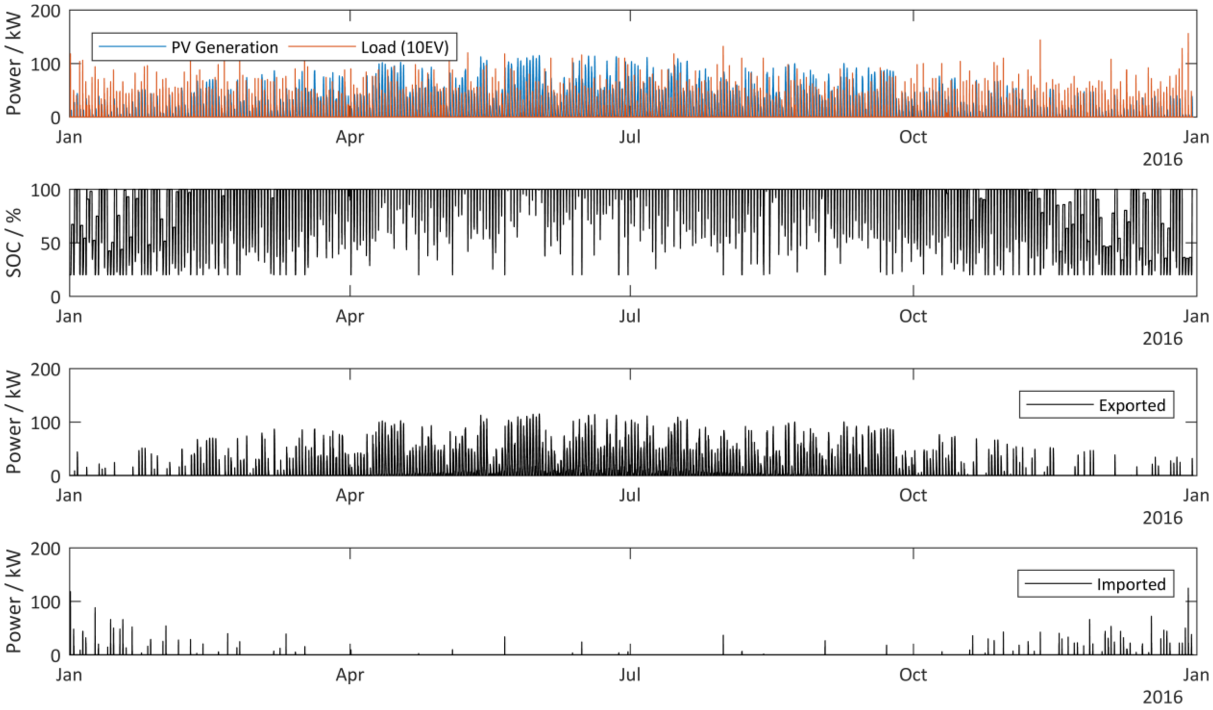


Figure 25: modelling output including grid import/export and support battery state.

A range of design cases were examined, looking at 1) the numbers of vehicles supported and 2) the size of the supporting battery. Additionally, two slightly system different operating strategies were analysed. The key performance variable analysed was the renewable utilisation fraction – i.e. the amount of electricity generated by the photovoltaic canopy that was used on site for EV charging, as opposed to being exported to the local electricity network. To understand how battery size and vehicle demand affected this metric a large number of parametric runs were made, varying the battery size and the number of vehicles using the charging hub. A typical output is shown below; this work indicated that there was no optimum battery size, bit there is a pronounced knee in the curve, beyond which increasing the battery size made little difference to the use of on sight renewable energy.

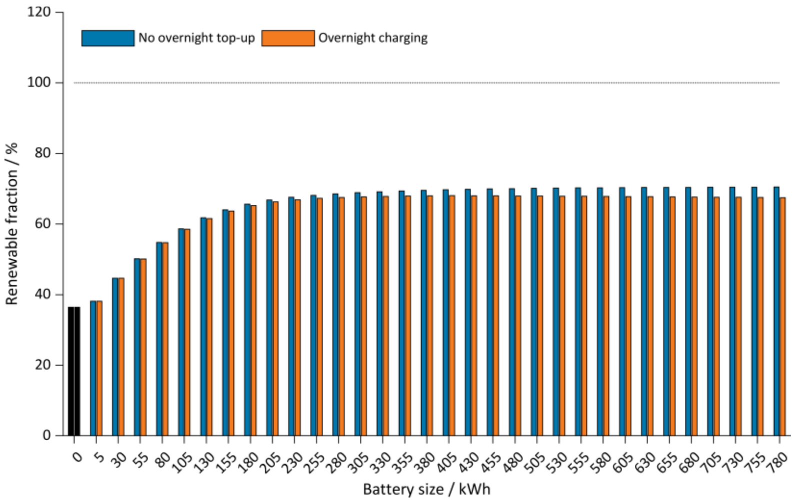


Figure 26: sensitivity analysis – battery size vs renewable fraction (fleet of 50 EVs).

The outcome from the modelling exercise was to supply the design team with key design parameter with which to select a battery to support vehicle charging and progress the design. A (rough) rule of thumb derived from the work was that that 6-10 kWh of battery capacity per EV serviced delivered the large majority of potential running cost savings and renewable utilisation fraction, whilst minimising the size of the battery required. The process is illustrated in Figure 27.

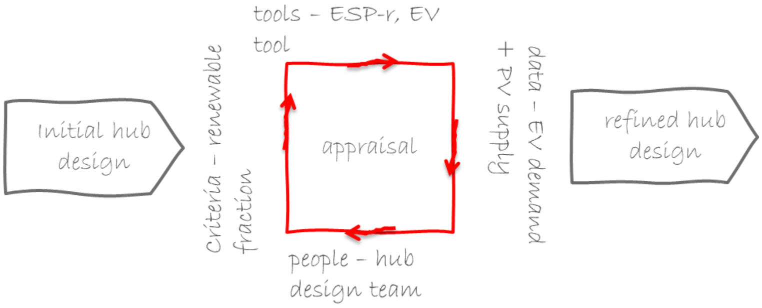


Figure 27: refining the hub design – specifying battery size.

8.1.3. Scaling Up

An important aspect of RUGGEDISED is assessing the impact of smart solutions a) at the larger scale and b) applied in the context of other cities. Consequently, the Glasgow charging hub model and tools were used to assess the potential impact of scaling-up the solution to other sites in Glasgow and then to Umea and Rotterdam. This required that the existing model was simulated against both Umea and Rotterdam datasets. The results were then normalised to the number of electric vehicle charges that could be supported by each 100m^2 of PV installation. In this case, an approximate measure of the number of vehicles supported by the can be found from:

annual vehicle charges = (area of PV / 100) × annual vehicle charges per 100m^2 of PV

The possible areas of PV that could be installed in the lighthouse cities are Glasgow – 8,235 m^2; Umeå – 11,048 m^2; and Rotterdam – 24,465 m^2.

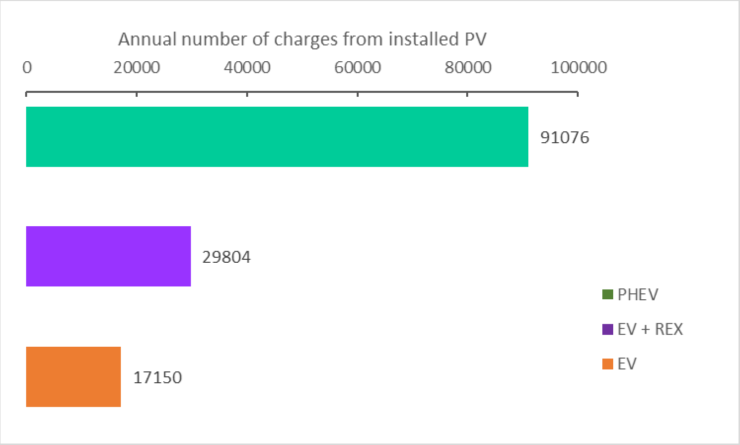
The number of vehicle charges supported is dependent on the type of electric vehicle as well as the prevailing climate as shown in Figure 28. The vehicles graphed are plug-in hybrid electric vehicles (PHEV), electric vehicles with range extension (EV + REX) and electric-only vehicles (EV). For reference the Glasgow case shown assumes that 8235m^2 of PV canopy is installed on car parks across the city.

The difference between the supported charges is due to the large variation in battery size between different vehicle types – ranging from an average battery capacity of 8.9 kWh on PHEV-type vehicles to 47.4 kWh for pure EVs.

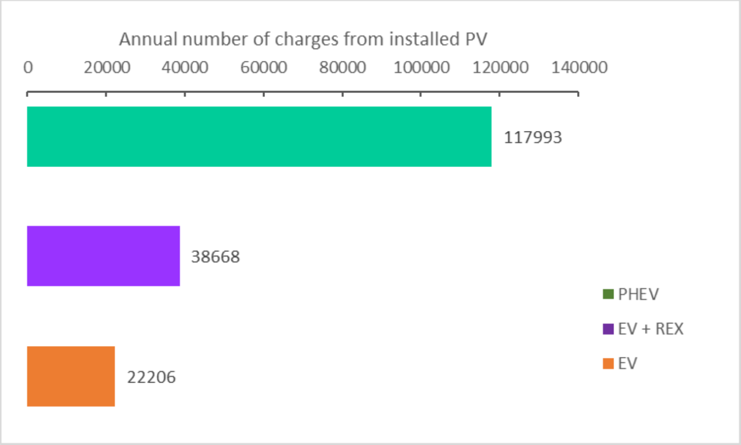
Using the published 2019 UK electricity carbon intensity of 277 g/kWh of electricity (Carbonfootprint, 2019), the Glasgow canopy and charging hub could save over 225 tonnes of carbon per annum. The figures for Rotterdam (carbon intensity 457 g/kWh) and Umea (12 g/kWh) are 1330 tonnes and 126 tonnes respectively.

The modelled data outlined above can act as an input to a decision point in the other lighthouse cities and shows that the same solution applied in different locations can have very different outcomes in terms of its environmental benefit.

Glasgow



Umea



Rotterdam

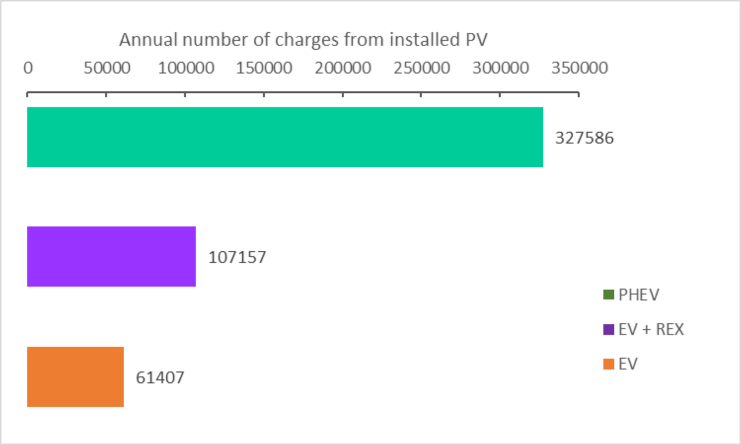


Figure 28: full vehicle charges supported by PV installed in Glasgow, Umea and Rotterdam, respectively.

8.2. Smart Heat Network

Rotterdam's R1 – R4 solutions entails the realisation a smart heat grid with the connection of different smart solutions to that grid – the aim is to move away from the usage of natural gas and improve overall energy efficiency. The main challenge of Rotterdam in implementing the integrated smart solutions is that the RUGGEDISED project is intensively intertwined with a large urban development project, a Public Private Partnership in the Hearth-of-South Rotterdam. The entire redevelopment of the area and the construction of new buildings was tendered in 2013, in an innovative way: the tender includes re-development/construction in tandem with a twenty-year maintenance contract for the area. A coalition led by Ballast-Nedam won the tender (with a budget of 330 million euros), the (re)-development project consists of:

- Demolition of the existing swimming pool and transformation of an existing office into a new swimming pool;
- Building of a theatre and library in one building on the old location of the swimming pool;
- Building of an international congress centre;
- Renovation of the existing exhibition centre Ahoy;
- Renovation of shopping mall and enlarging it;
- Building of 100 houses;
- Renovation of the existing bus-station and roads, new space for small enterprises;
- Transformation of Gooilandsingel into pedestrian area;
- Renovation of public space around Zuidplein/Ahoy.

Smart solution R1 is the Smart Thermal Grid in the Heart of South-redevelopment project in Rotterdam. Smart solutions R2, R3 and R4 are also part of this development; The project partners aimed to realise the following solutions that consist of a thermal heat and cooling exchange grid with seasonal storage (R1), energy from waste water (R2), energy exchange with surface water (R3) and a pavement heat-cold collector (R4). All buildings would (eventually) be connected by the conventional high temperature district heating grid and a low temperature heating- and high temperature cooling-grid and each connected building would have a heat pump on-site to be able to reach the demanded heat and cooling requirement. Because of the diversity of functions of the connected buildings and the energy sources, and the involved peak demands during different times translates to a lower total base load. This would save on installation costs as the capacity can be lower.

The initial Description of Work included the following buildings/facilities to be connected to the Smart Heat Network:

- The existing and new parts of the exhibition centre Ahoy;
- The new Congress Centre (building in progress);
- The new Arts building (building in progress);
- The new 50-m swimming pool (building completed);

(And in a later phase)

- The cinema;
- The hotel;
- The hospital Ikazia.

However, Ballast-Nedam asked Eneco to take over their responsibilities as the development of the Smart Heat Network was not part of their core business. The agreements in the PPP Heart of South were revised accordingly. In the current agreement, Eneco is responsible for developing the Smart Thermal Grid and its connected smart solutions (R1 – R4). The municipality of Rotterdam took over the technical coordination tasks. Due to these complications and a delay in the development of buildings, R1 is currently partly finished, R2 is still in development, R3 was firstly left out due to feasibility problems, but is now again in sight with a different approach and R4 is in development at another location.

Additionally, the revised description after the amendment of the Smart Thermal Grid focusses on the following buildings:

- Existing AHOY exhibition Centre *(connected)*
- New Congress Centre (ICC) *(soon to be connected)*
- Cinema *(not in current phase)*
- Hotel *(not in current phase)*

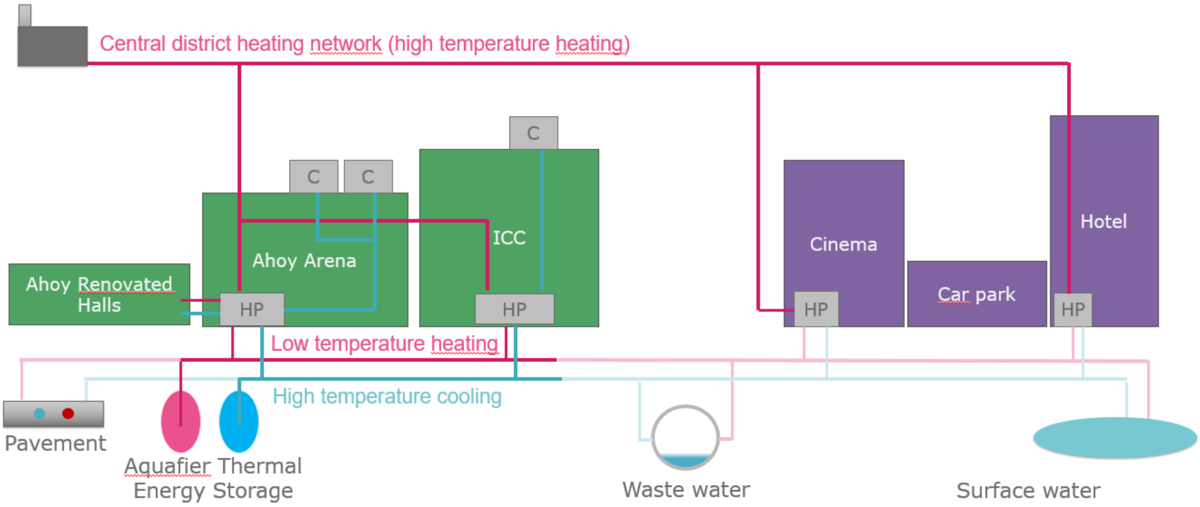


Figure 29: diagram showing the Rotterdam Smart Thermal Grid network.

Different amendments had thus to be made to the initial project plans:

- The 50-meter swimming pool was not connected to the Smart Thermal Grid, but to the District Heating network, due to a mismatch in project planning and a too long distance.
- Due to the distance between the Arts building and the Smart Thermal Grid, a connection was not made as a business case could not be made.
- The cinema, the hotel and the parking garage were not included in this phase of the Smart Thermal Grid;

Working on two intertwined projects simultaneously is very challenging. As mentioned earlier, RUGGEDISED is executed on top of the (re)development of the Heart of South-area. The two projects have different time schedules and phases, including other (third) parties that are not formal RUGGEDISED partners and already have pre-existing contracts. It turned out to be a very challenging process to operate on top of existing contracts. Especially the ones in which the finances are already fully arranged

8.2.1. Windows of opportunity

The success of smart city projects highly depends on path-dependencies. In this case the path dependency is clear: the Heart of South-planning certainly prevents certain business cases to be viable and prevent the realisation of projects due to strict project planning. The interaction between the two projects is even further troubled by the work that is already completed. In deliverable D1.2 (RUGGEDISED, 2017) the term 'windows of opportunity' (Kingdon, 1995) was used to emphasize that smart city solutions are characterized by interconnectivity and embeddedness within their urban environment; whilst the term is mostly used to describe policy processes it also applies to the realization of smart solutions and the direct relation with troubling project timeframes and non-cooperating project phase intervals.

The implementation of the smart solutions therefore relies partly on the right connection between different levels and departments within the municipality, Ballast-Nedam, Eneco and the other parties involved. The fact that some of the smart solutions have not yet been realised and some buildings have not yet been connected to the Smart Thermal Grid, does not mean these solutions will never be implemented. Currently studies are being executed for a future phase (outside the scope of RUGGEDISED): upscaling the Smart Thermal Grid towards the hospital Ikazia, and existing apartment buildings nearby. The current business case looks promising.

8.2.2. Evolutionary path for smart solutions: connecting projects trough intensive project-phase modelling

As can be seen from this illustrative study addressing the Smart Heat Network, not only the newly added Renewable Energy Sources (RES) and abated carbon emissions are of importance when addressing smart city designs or making decisions regarding smart solutions and tools. Also other projects (and the involved people) simultaneously occurring in the area need to be explored and established. This should lead towards integrated modelling of all project phases, forthcoming windows of opportunity and bottlenecks. As was discussed in D1.3 Lessons Learned in the Lighthouse cities (1/3) (RUGGEDISED, 2018), smart city developments never start from scratch, they result from history and diverging interests that together produce urban policies.

This illustrative study emphasizes that much importance and emphasis should lie in exploring each timelines, contracts and interests of all involved projects and partners in the area, not only the RUGGEDISED project partners. Modelling in this sense is crucial for the realization, connection and upscaling of smart solutions.

The modelling described in this section is mainly of importance in stage in the phases selected concept design and appraisal as raised in chapter 3. Even before determining the exact technological specifics it is of crucial importance that other projects and parties are well explored and determined as they can greatly impact technological possibilities, business cases, usefulness, feasibility and project planning (among other aspects).

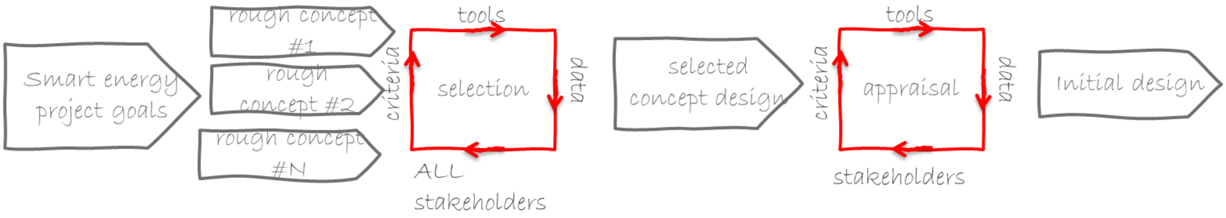


Figure 30. Elements of the SEDP in the Rotterdam project.

8.2.3. Energy reduction & CO_2-reduction

The expected impact of the Smart Thermal Grid is a yearly reduction of energy demand of 1,2 million kWh and a CO2 reduction of 282 tonnes with the proposed smart solutions R1-R4. The Smart Thermal Grid is supplying heat in cooperation with the district heating network. In Rotterdam a part of the city is already connected to district heating, the heat is mainly derived from a waste incineration plant at the Port of Rotterdam.

8.2.4. Scaling up

In the future, other buildings e.g. the cinema, hotel and hospital can be connected to this grid, as well as a variety of other energy sources will be connected. The viability of the business depends on the upcoming renovation works. The current business case looks promising.

8.3. Smart Office

The aim of the Umeå smart office solution (U4) is to reduce energy consumption in office buildings by using automatic control of ventilation, heating, cooling and lighting. This is done by measuring presence, temperature and carbon dioxide in each room by a multi sensor. The modelling activity undertaken here is to prove the concept and also extrapolate the results to the other Lighthouse cities in order for them to make a judgment as to the viability of the solution in their own city.

8.3.1. Modelling of the Umeå system

To evaluate the effects of this solution a MATLAB building simulation model was developed to calculate the energy consumption of a general office building in the lighthouse cities. The model accounts for electricity, cooling and heating consumption. The office building model was assumed to be of 3200 m^2 floor area and each employee is assumed to have 20 m^2 (Sveby, 2013). A 70 % occupancy of the office is assumed during weekdays and working hours, 8-17 (Sveby, 2013). The office is serviced by a constant air volume (CAV) heating, ventilation and air conditioning (HVAC) system.

The basic model has been adapted to represent the implementation of the smart control equipment that is demonstrated in one of the University buildings in Umeå which makes it possible to control lighting and indoor climate through the ventilation and heating and cooling systems and also makes it possible to compare the energy demand before and after the implementation.

With reference to the smart energy district planner, what is described here is a proof of concept, prior to a more extensive design of the control technology.

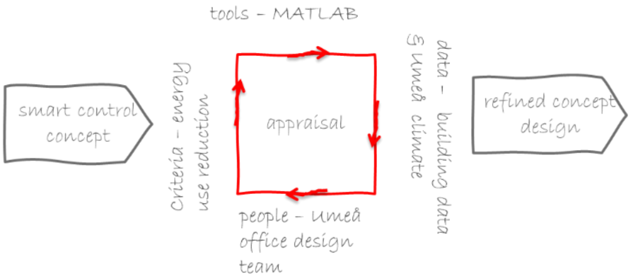


Figure 31. Evaluation of smart office control concept.

8.3.2. Umeå system analysis

The smart control equipment turns off the light when no occupancy is detected in the room. The air flow is also regulated with respect to occupancy in the room, with two levels of air flow during 7-19 at workdays. It is assumed that the air flow is zero outside of these hours. The heating and cooling systems is regulated to keep the temperature within 21-23 °C. The model does not capture seasonal and daily variations in occupancy due to vacations and movement of people within the building which makes some offices empty during meetings for example. Therefore, it is likely that the energy reduction of this solution is even larger than captured with this model.

The transmission factors of the building envelope used for the buildings in Umeå are presented in **Error! Reference source not found.**.

Table 2. Transmission factors used for the building envelopes in Umeå (Sveby, 2013).

U_{roof} [W/m^{2}K]	U_{ground} [W/m^{2}K]	U_{window} [W/m^{2}K]	U_{wall} [W/m^{2}K]
0.19	0.32	1.2	0.32

The climate data used as input to the model is normalised data for the year 2017 in Umeå, developed by (Sveby, 2019). The outside temperature and the solar radiation are presented in **Error! Reference source not found.**. The mean temperature in Umeå is 4.0 °C and the mean solar radiation is 92.0 W/m^2.

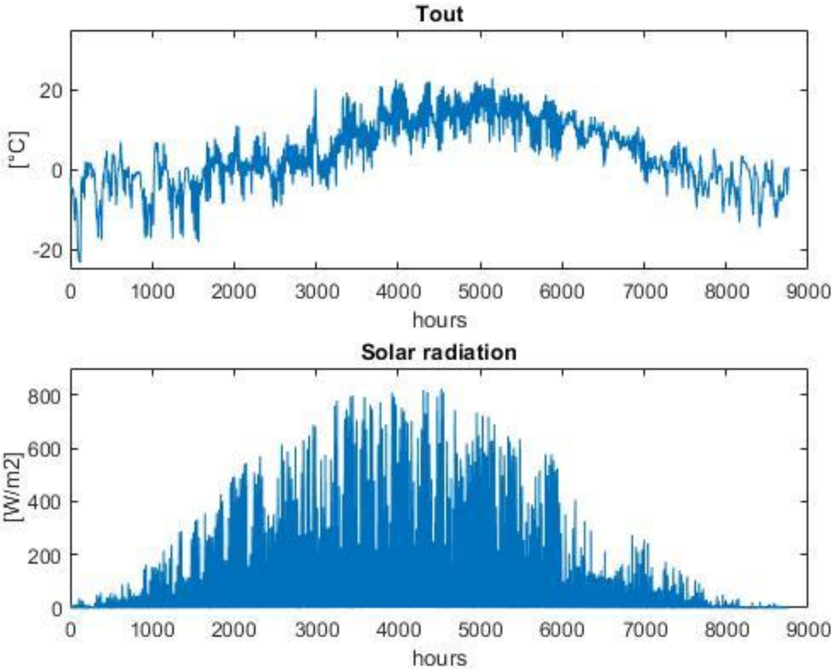


Figure 32. Temperature and solar radiation in Umeå with hourly resolution (Sveby, 2019).

Error! Reference source not found. The heating demand increases when the solution is implemented. This is due to the reduction in electricity demand since the lighting control reduce heat emitted by the lighting. The total energy demand per m^2 reduces with 16%.

Table 3. Comparison of energy demand for office building in Umeå before and after implementation of smart control equipment.

	Baseline	Smart control equipment	Difference
Cooling [kWh/m^2]	26.15	15.89	-39%
Heating [kWh/m^2]	62.47	63.42	2%
Electricity [kWh/m^2]	57.91	43.29	-25%
Total [kWh/m^2]	146.5	122.6	-16%

The U4 solution is assumed to be replicable to 75% of the office buildings in the city, according to the scenarios. It is not implemented in residential buildings since the sensors and equipment is quite expensive. Therefore, it is diffused to 75% to buildings with business functions. Nevertheless, the demonstrations of the U4 solution in Umeå is taking part in the university, which is buildings classified as civic functions. Therefore, it is assumed that also 50% of the buildings with civic functions has the possibility to implement a solution like this. The upscaling potential of this solutions is an energy reduction of 23 GWh/year in Umeå.

Table 4. Energy reduction potential when upscaling the U4 solution in Umeå.

	Heating	Cooling	Electricity	Total
GWh/year	0.91	- 9.81	-13.98	- 22.88

The model has adapted to each lighthouse city by using climate data and U-values for each city. The data and results for each city is presented separately in the following sections.

8.3.3. Glasgow system analysis

The smart office solution was applied to an equivalent Glasgow office building and using Glasgow climate data, the results are presented in Table 5**Error! Reference source not found.**. As can be seen, the reduction of cooling demand is up to 40% and the heating demand increases with 12% while the total energy demand reduces with 19%, which is 23.17 kWh/m^2 in absolute values.

Table 5. Comparison of energy demand for office building in Glasgow before and after implementation of smart control equipment.

	Before	Smart control equipment	Difference
Cooling [kWh/m^2]	31.02	18.76	-40%
Heating [kWh/m^2]	31.81	35.52	12%
Electricity [kWh/m^2]	58.18	43.55	-25%
Total [kWh/m^2]	121	97.83	-19%

The overall office space floor area in Glasgow city centre is approximately 1,000,000 m^2 and 10% of these are estimated to be modern buildings with the possibility to implement this solution. The potential energy reduction of upscaling U4 solution to this office area is presented in **Error! Reference source not found.**. The heating demand increases when the solution is implemented while the demand for cooling and electricity reduce. The total energy demand for offices in Glasgow city centre reduces by 2.33 GWh/year.

Table 6. Energy reduction potential when upscaling the U4 solution in Glasgow.

	Heating	Cooling	Electricity	Total
GWh/year	0.37	- 1.23	-1.47	- 2.33

8.3.4. Rotterdam system analysis

The energy demand for an office building located in Rotterdam is calculated with the same basic assumptions as for the office in Umeå but with appropriate construction information and climate data for Rotterdam as input. The results are presented in **Error! Reference source not found.** where it can be seen that the reduction of cooling demand is 35% and the heating demand increases with 9%. The total energy reduction is 20%.

Table 7. Comparison of energy demand for office building in Rotterdam before and after implementation of smart control equipment.

	Before	Smart control equipment	Difference
Cooling [kWh/m^2]	40.79	26.71	-35%
Heating [kWh/m^2]	29.21	31.81	9%
Electricity [kWh/m^2]	57.63	43.01	-25%
Total [kWh/m^2]	127.63	101.53	-20%

The total office floor area in Rotterdam is approximately 3.62 million m^2. The potential energy reduction of upscaling U4 solution to this office area is presented in **Error! Reference source not found.**.

Table 8. Energy reduction potential when implementing and upscaling U4 solution to the office floor area in Rotterdam.

	Heating	Cooling	Electricity	Total
GWh/year	1.88	- 10.19	- 10.58	- 18.89

9. Post Installation Comparison

All of the smart solutions design examples cited previously highlight simulated (i.e. predicted) performance. However, the role of modelling does not end with the realisation of a design. Modelled data can be of use post installation or post construction.

9.1. Post Installation Evaluation

The latter stages of RUGGEDISED include a significant amount of effort in monitoring the performance of smart solutions. Modelled data can be useful in that it provides a baseline against which to assess the performance of the smart solution in-situ. If the performance of the installed system is significantly poorer the model, then that would indicate that either a) there is a technical problem with operation of the smart solution or b) the model predictions were wrong and there are errors in the model and/or in the assumptions used to develop the model and simulate performance.

9.1.1. Improving the Accuracy of Models

Predicting the performance of smart solutions such as those developed in RUGGEDISED is a difficult task given the complexity and novelty of the systems being modelled. Where there is significant discrepancy between the simulated performance of a smart solution and the actual performance of the solution in situ, the most likely cause is a problem with the model. These can include the following.

Table 9. Types and examples of modelling error.

Error	Example
an intrinsic error in the underpinning technical model of the solution or a specific technology;	a bug in software causing a numerical algorithm to produce incorrect results under certain operating conditions
extrinsic errors or discrepancies in the data used to calibrate or simulate a model;	historical climate data used to calculate the output from renewable energy device being significantly different from the actual climate experienced during the monitoring process

errors in the assumptions underpinning the operation of a smart solution.	where the assumed occupancy of an office building featuring energy efficient technologies turns out to be completely different from that assumed in the modelling process
user errors	where data entered for a model is incorrect or where the wrong model is used

Monitored data can be useful in improving the predictive accuracy of models. The availability of this monitored data and comparative analysis with the original modelled data provides the opportunity for models, assumptions or input data to be corrected if significant discrepancies are found to occur. For example, Monari (2016) outlines an approach, where monitored data can automatically be used to calibrate a simulation model and also to pinpoint possible sources of error in the model data.

In RUGGEDISED the ability to correct predictive models will be of particular use to the follower cities as the move forward with their own designs. The comparison of measured and modelled data and any subsequent remedial action required either to the models, data or underpinning assumptions, will build confidence in the modelling process.

9.1.2. Guiding Remedial Actions on Smart Solution Interventions

Where there are no problems identified with the model or in the data and assumptions used to run the model then this would indicate that there may be a problem with the operation of the smart solution and that remedial action may be needed to improve performance. The modelled data may be a useful means to pinpoint where the problem in performance may arise.

As an illustration, the building modelling tool ESP-r was used to model the performance of domestic air source heat pumps prior to a long term field trial in Scottish social housing (Kelly and Cockroft, 2011). This indicated that an annual coefficient of performance (COP) of more than 2.5 was achievable in typical climate and usage conditions. However, the performance of the heat pumps when installed was poorer than the model suggested. There was a significant discrepancy between the modelled and measured COP in that at higher ambient temperatures the modelled COP was significantly better than the measured COP (Figure 33).

Subsequent investigation revealed that this was due to fact that the model accounted for temperature compensation: a process where the flow temperature to the heating system served by the heat pump is reduced as ambient temperatures rise and the heating load drops; this boosts improves the COP as the ambient temperature increased. Temperature compensation had not been activated on the installed heat pumps. Remedial action, namely activating this feature on the heat pumps under test improved performance.

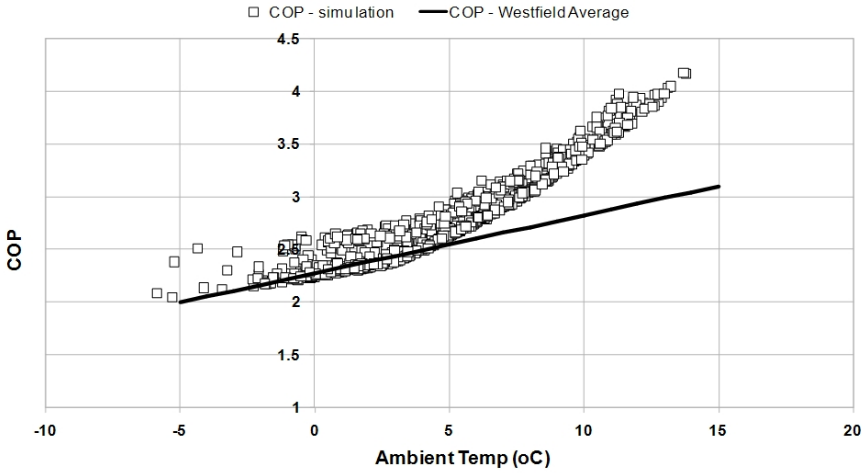


Figure 33. Discrepancy between modelled and monitored data (Kelly and Cockroft, 2011).

10. Conclusions

The various city teams behind RUGGEDISED are tackling complex problems with regards to developing demonstrations of zero-carbon concepts in the Lighthouse cities. The novelty and complexity of many of the systems underpinning the smart solutions mean that modelling is used to provide input to design and decision making processing from the outset.

This report has set out the idea of a “smart energy district planner” (SEDP), which is a combination of modelling tools and processes that can assist a RUGGEDISED city team in making well-informed design decisions based on data from a suite of modelling tools. An illustrative design path is developed, the core of which are the decision points. The criteria, tools, data and (importantly) people required to make a robust decision are key to these. Each aspect of decision support is examined in detail, which descriptions of the type of models available provides, information on sources of data provides, different criteria for decision making illustrated and information on selection of key stakeholders provided.

Three illustrative examples of model-supported smart solution design from each of Lighthouse cities are provides, illustrating the use of modelling tools, how data from these models helped inform the design decision and the modelled performance of the smart solutions.

The report ends with an explanation of how the completion of the smart solutions is not the end of the modelling process: how models can be used to pinpoint problems in portly performing solutions and monitored data from solutions can be used to improve the veracity of models.

The prototype SEDP is intended to be used by the follower cities, enabling them to learn from the experiences the lighthouse cities. It also providing those cities with the means (through use of the developed tools and processes) to make more robust design decisions with regards to the development of their own smart solutions. To this end, information on the tools used in the modelling process and information on access to those tools (where practicable) is also provided in the Appendices (section 12).

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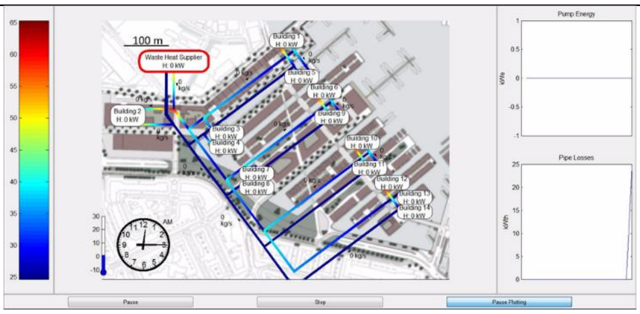
12. Appendices

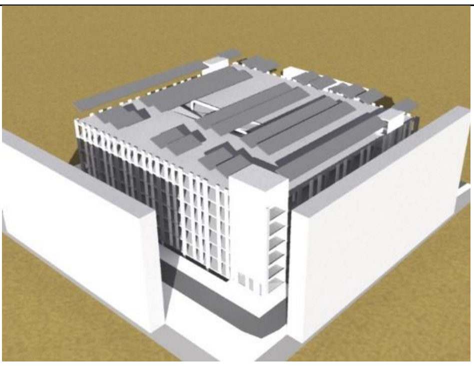
12.1. Directory of RUGGEDISED Modelling and Evaluation Tools

12.1.1. CHESS

Software name:	CHESS
Compiled by:	Martijn.clarijs@tno.nl
Software type:	Thermal network
Licence type:	In-house usage, stand-alone beta version license
Compatible operating systems:	Windows
Brief description:	CHESS is a MATLAB based software tool for conceptual analysis and optimization of thermal networks. It consists a.o. of a thermal solver, flow solver, component libray and GUI. Fast simulations and accessible results to user are provided via KPI dashboard (in progress); drag-drop GUI for model building. Important component models (Geo. Well, ATES, Heat Pump, PV Panels etc.) are available. Innovative and user-friendly features/application such as GIS-based grid design, topology optimization and smart control algorithms are working in conjunction with CHESS
Application (s) in RUGGEDISED:	CHESS has been used to check features from a preliminary design of the Smart Thermal Grid in RUGGEDIZED. To this purpose, the flow velocities in the pipelines were calculated for a sanity check, and several scenarios with hot/cold supply to the system were simulated, supporting decisions w.r.t. dimensioning components and pipelines in the design.
Link to software or further information:	Martijn.clarijs@tno.nl
Image:	
Caption:	CHESS screenshot from a simulation of district heating system

12.1.2. ESP-r

Software name:	ESP-r

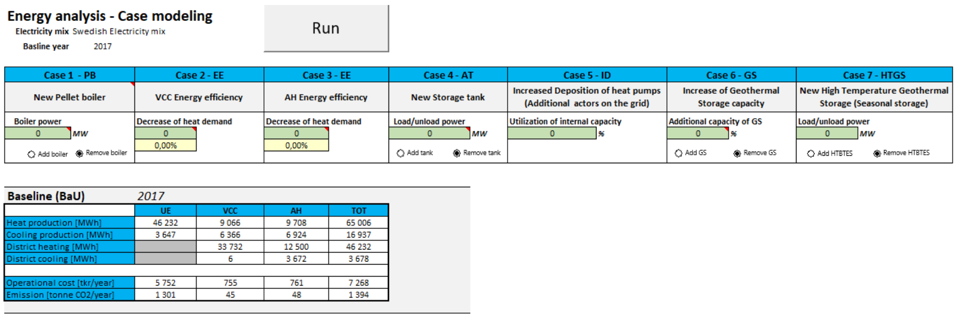
Compiled by:	Nick Kelly (nick@esru.strath.ac.uk)
Software type:	Building simulation tool
Licence type:	Open Source
Compatible operating systems:	Linux, Windows 10 (with Ubuntu support), MacOS
Brief description:	ESP-r is a whole building energy simulation program for integrated modelling of building energy performance. The tool can be used to model one or multiple buildings and the energy systems that support them. The primary application of the program is to support researchers and designers undertaking detailed energy modelling studies.
Application (s) in RUGGEDISED:	Modelling of thermal load shifting in residential buildings Modelling of photovoltaic (PV) canopy performance Modelling of district heating piping systems
Link to software or further information:	http://www.esru.strath.ac.uk/Programs/ESP-r.htm
Image:	
Caption:	ESP-r model of the Glasgow smart solution G4 – PV canopy on Duke St Car Park.

12.1.3. Energy Analysis - Case Modelling Tool

Software name:	Energy Analysis – Case Modelling Tool
Compiled by:	Allan Rydman (allan.rydman@sweco.se)
Software type:	Data visualisation and modelling
Licence type:	Microsoft Office
Compatible operating systems:	Windows 7-10

<table>
<tr><td>Brief description:</td><td>Excel VBA was used to create a main function and sub functions. The main function utilizes the predetermined production unit’s hourly production capacity to simulate production data to meet the hourly demand of heating and cooling defined by the baseline. Default conditions that limit unit production that exist through technical or business limitations are defined in the main function. Sub functions define different investments that in different ways alter the conditions of the main function and, when applied, yields different sets of simulated production data.

The resulting difference in calculated cost and emissions compared to baseline can be valued in a business analysis to promote or oppose investments and business models.</td></tr>
<tr><td>Application (s) in RUGGEDISED:</td><td>Modelling of heat and cooling production data

Modelling of cost and emission of heat and cooling production</td></tr>
<tr><td>Link to software or further information:</td><td></td></tr>
<tr><td>Image:</td><td>


Energy analysis - Case modeling
Electricity mix Swedish Electricity mix
Basline year 2017

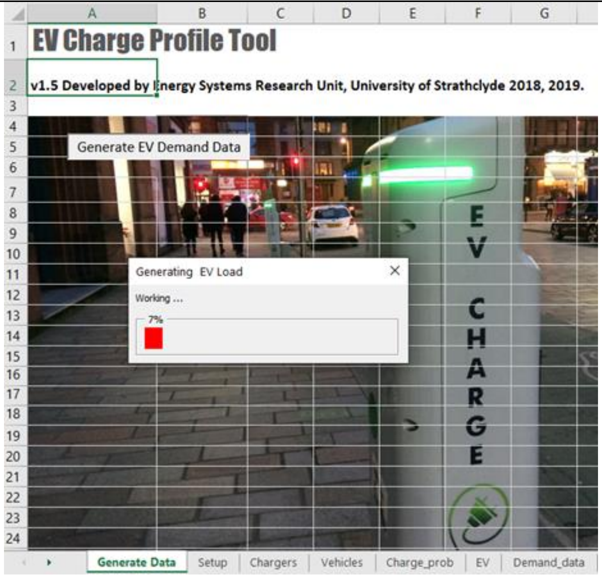
<table>
<tr><th>Case 1 - PB</th><th>Case 2 - EE</th><th>Case 3 - EE</th><th>Case 4 - AT</th><th>Case 5 - ID</th><th>Case 6 - GS</th><th>Case 7 - HTGS</th></tr>
<tr><td>New Pellet boiler</td><td>VCC Energy efficiency</td><td>AH Energy efficiency</td><td>New Storage tank</td><td>Increased Deposition of heat pumps (Additional actors on the grid)</td><td>Increase of Geothermal Storage capacity</td><td>New High Temperature Geothermal Storage (Seasonal storage)</td></tr>
<tr><td>Boiler power</td><td>Decrease of heat demand</td><td>Decrease of heat demand</td><td>Load/unload power</td><td>Utilization of internal capacity</td><td>Additional capacity of GS</td><td>Load/unload power</td></tr>
<tr><td>0 MW</td><td>0</td><td>0</td><td>0 MW</td><td>0 %</td><td>0 %</td><td>0 MW</td></tr>
<tr><td></td><td>0,00%</td><td>0,00%</td><td></td><td></td><td></td><td></td></tr>
<tr><td>○ Add boiler ● Remove boiler</td><td></td><td></td><td>○ Add tank ● Remove tank</td><td></td><td>○ Add GS ● Remove GS</td><td>○ Add HTBTES ● Remove HTBTES</td></tr>
</table>

Baseline (BaU) *2017*

<table>
<tr><th></th><th>UE</th><th>VCC</th><th>AH</th><th>TOT</th></tr>
<tr><td>Heat production [MWh]</td><td>46 232</td><td>9 066</td><td>9 708</td><td>65 006</td></tr>
<tr><td>Cooling production [MWh]</td><td>3 647</td><td>6 366</td><td>6 924</td><td>16 937</td></tr>
<tr><td>District heating [MWh]</td><td></td><td>33 732</td><td>12 500</td><td>46 232</td></tr>
<tr><td>District cooling [MWh]</td><td></td><td>6</td><td>3 672</td><td>3 678</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Operational cost [tkr/year]</td><td>5 752</td><td>755</td><td>761</td><td>7 268</td></tr>
<tr><td>Emission [tonne CO2/year]</td><td>1 301</td><td>45</td><td>48</td><td>1 394</td></tr>
</table>
</td></tr>
<tr><td>Caption:</td><td>Technical production data model of the smart solutions U1 – Smart City connection to 100% renewable energy and U3 – Geothermal heating/cooling storage.</td></tr>
</table>

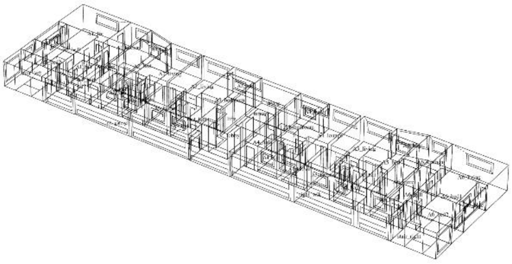
12.1.4. EV Charging Tool

Software name:	EV charge tool
Information compiled by:	Nick Kelly (nick@esru.strath.ac.uk)
Software type:	Profile generation: EV charge
Licence type:	Freely available
Compatible operating systems:	Windows (VBA programme - requires Excel)

Brief description:	The charge tool is based around vehicle charging probability time profiles, derived from real charge point data. For a user-defined set of vehicles and charge points the tool will calculate the charging demand at half-hour time intervals for a user defined period. It also tracks the occupancy of each charge point and the charge state of each vehicle.
Application (s) in RUGGEDISED:	Performance modelling of PV-supported charging hub.
Link to software or further information:	Available on request from esru@esru.strath.ac.uk
Image:	 EV Charge Profile Tool v1.5 Developed by Energy Systems Research Unit, University of Strathclyde 2018, 2019. Generating EV Load Working ... 7%
Caption:	Screen shot of the EV charging tools sohwing an EV charging point in glasgow city centre.

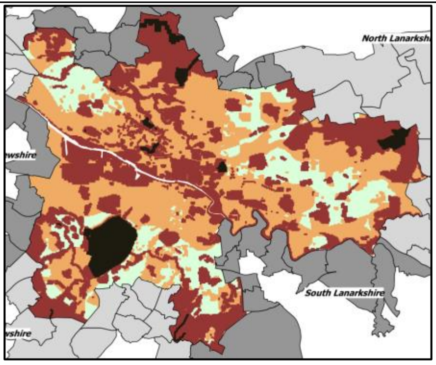
12.1.5. Household Profile Tool

Software name:	Household Profile Tool
Information compiled by:	Nick Kelly (nick@esru.strath.ac.uk)
Software type:	Profile generation: household occupancy, hot water demand and small power demand
Licence type:	Freely available (Python)
Compatible operating systems:	Windows, Linux, MacOS
Brief description:	The tool used socio-economic data (e.g. time use survey data) to calibrate statistical models for domestic occupancy, hot water use and small power use. The tool can generate a diversified set of distinct profiles for one or more dwellings at time resolutions as fine as 1-minute. The profiles can be used by building simulation tools or power system modelling tools.

Application (s) in RUGGEDISED:	Modelling of Drygate flat heating systems performance and battery supported load shifting.
Link to software or further information:	Available on request from esru@esru.strath.ac.uk
Image:	
Caption:	Drygate flat model: which used occupancy profiles in the caclulation of heating system performance.

12.1.6. QGIS

Software name:	QGIS
Software type:	Geographical information system
Compatible operating systems:	Linux, Windows 10, MacOS, BSD
Brief description:	"QGIS functions as geographic information system (GIS) software, allowing users to analyze and edit spatial information, in addition to composing and exporting graphical maps. It supports both raster and vector layers; vector data is stored as either point, line, or polygon features. Multiple formats of raster images are supported, and the software can georeference images. QGIS supports shapefiles, coverages, personal geodatabases, dxf, MapInfo, PostGIS, and other formats. Web services, including Web Map Service and Web Feature Service, are also supported to allow use of data from external sources. QGIS integrates with other open-source GIS packages, including PostGIS, GRASS GIS, and MapServer."
Application (s) in RUGGEDISED:	Glasgow smart solution design support.
Link to software or further information:	https://www.qgis.org/en/site/

Image:	
Caption:	QGIS map showing areas suitable for PV installation on derelict land in Glasgow.

12.1.7. MATLAB

Software name:	MATLAB
Information compiled by:	Nick Kelly (nick@esru.strath.ac.uk)
Software type:	General purpose modelling software.
Licence type:	Commercial software
Compatible operating systems:	Windows
Brief description:	MATLAB is a general purpose numerical modelling software that can be applied to the analysis of a broad range of technical domains.
Application (s) in RUGGEDISED:	Modelling the behaviour of office buildings when subjected to smart control.
Link to software or further information:	http://mathworks.com
Image:	n/a
Caption:	n/a

12.1.8. RADIANCE

Software name:	RADIANCE
Information compiled by:	Nick Kelly (nick@esru.strath.ac.uk)
Software type:	Lighting simulation tool
Licence type:	Open Source
Compatible operating systems:	Windows, Linux, MacOS

Brief description:	Radiance is a suite of programs for the analysis and visualization of lighting in design. The input includes the geometry of the scene to be visualised, materials, luminaires, time, date and sky conditions (for daylight calculations). Calculated values include spectral radiance (ie. luminance + colour), irradiance (illuminance + colour) and glare indices. Simulation results may be displayed as colour images, numerical values and contour plots. As RADIANCE is derived from basic lighting physics. there are few limitations on the geometry or the materials that may be simulated. Radiance is used by architects and engineers to predict illumination, visual quality and appearance of innovative design spaces, and by researchers to evaluate new lighting and daylighting technologies.
Application (s) in RUGGEDISED:	Radiance has been used to render building simulation models and investigate shading on PV canopies. It has also been applied to the analysis of smart street lighting.
Link to software or further information:	https://www.radiance-online.org/
Image:	
Caption:	Radiance rendering of Duke St. flats.