REEMAIN
RESOURCE AND ENERGY EFFICIENT MANUFACTURING

EFFICIENCY ANALYSIS METHODOLOGY

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Executive Summary

This deliverable describes the various elements of a methodology for modelling the energy generated and used by the different parts of an industrial energy system, in REEMAIN. This is necessary to analyse the efficiency of the industrial energy system in order to identify the improvements that can be delivered by the integration of renewable energy systems, the use of technology for waste energy capture and the derivation of more energy efficient manufacturing schedules.

Chapter 1 of the deliverable presents the resource networks methodology developed by Fraunhofer IWU, which is a conceptual tool to deal with the complexity of integrating renewable energy systems into manufacturing systems, while respecting the realities of material flows, processing requirements, grid constraints and personnel capabilities. Chapter 2 describes a means by which energy demand profiles may be conceptualised, captured from reality and modelled. This chapter also explains how the different combinations of heating and cooling requirements of processes within the factory give rise to a range of demand profiles whose shape can significantly impact the efficiency of energy systems. This is why the concept of rough-cut demand modelling developed in D3.3 is so important to REEMAIN. The chapter closes with a description of the use of discrete event simulation as a tool for modelling industrial energy demand. Chapter 3 covers the various theories and empirical approaches that underpin the models of the renewable energy technologies selected for inclusion in REEMAIN, including solar PV, solar thermal collectors, solar concentrators, hot water storage, Lithium-ion batteries, solar cooling systems, combined heating, power and cooling and the organic Rankine Cycle. Chapter 4 explains how these discrete models of selected technologies may be integrated to create a model of an energy system that can be used to explore the dynamic efficiency of the complete energy system. Chapter 5 describes and compares a range of commercially available modelling tools that may be used to create dynamic models of the energy supply technologies, the components of new energy systems and the demand from the factory; as well as the means of exchanging data between different tools. Finally chapter 6 consolidates the previous chapters by presenting the results of discussions between the authors in the form of a suggested modelling approach that will be developed and refined through the rest of the tasks within work package 4.

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1. Introduction

This deliverable is an opening deliverable of REEMAIN's work package 4. The WP4 main objectives are described in the project's description of work (DoW) document as:

"WP4 will develop the scientific and technical methodology that ensures seamless implementation of energy efficiency measures and technologies while considering the efficient use of resources, i.e. material, personnel, machine capacities, and corresponding technologies within the factory. The resulting methodology for planning and controlling the technologies is aiming for minimal emission and cost-effectiveness within the factory with respect to external as well as internal, ecological and economical influences." …. "The target is to achieve the factories to be fully resource efficient and evolve towards zero-carbon emissions."

Task 4.1 deals with measurement and modelling methodologies for continuous energy use, and it has been led by De Montfort University (DMU). The DoW broadly defined the task's main objectives as well as proposed steps to complete these objectives:

"In this task a methodology for the measurements of continuous flow of energy and material will be defined, which will allow the modelling of factory control mechanisms based on the results of WP1 and WP2. This in turn, will facilitate the evaluation of the efficiency for the resource usage (energy, material, …) within and around the factory. This efficiency measurement will be based in a collection of data from the entire manufacturing system; which may include the supplier, sub-contractors, customer delivery and waste processing functions where these influence the resource flows within the factory."

In a series of meetings between DMU and Fraunhofer IWU, both conference calls and in person; and with the approval from the project coordinator CARTIF, we agreed that factory control mechanisms will actually be related to controlling the source efficiency. This mainly concerns the selection of suitable renewable energy systems (RES) and their optimal operation and integration with the existing energy system. The second step in the control mechanism will be to optimise the manufacturing system (scheduling, buffer, etc.) to maximise the performance of proposed integrated RES.

According to the DoW, the efficiency measurement methodology developed in task 4.1 should provide the basis for developing the planning and control mechanisms for the resource networks described in T4.2 and T4.3. Three major steps have been identified in the DoW:

1. *"The measured data on process level (described in WP1, WP2) will be used to develop measures for material and energy efficiency at the factory level. This measurement should not necessarily require the use of information technology, since this will not always be available in a suitable form."*

Strictly speaking, the measured data at process level can only be used as input parameters for the factory (primary system) energy efficiency analysis and these are crucial pieces of information required for evaluating performance. However, in the absence of measured data, we will also be able to generate energy profiles required for the analysis by either applying the rough-cut methodology developed in work package 3 (T3.3) or by using specialised manufacturing process modelling tools such as Siemens Plant Simulation (see section 5.3.2).

2. *"The factory efficiency measures will be compared within a range of best-case and worst-case scenarios, i.e. energetic/material efficiency benchmark of the factory KPIs. This comparison highlights the impact upon resource efficiency of flows of energy and material in the factory compared to an ideally optimised manufacturing system."*

The selection of the most suitable low carbon energy generating system, to replace or augment the current conventional system, will be based on the typical operation profiles (energy demands), while the potential improvements will be evaluated by varying the operation profiles in order to maximise the performance of applied systems.

3. *"This enables the continuous control of the energy and material flows in a more continuous manner towards the twin goals of resource efficiency and reduced carbon emissions. The methodology gives guidance for improved integration of energy using manufacturing technologies and their supporting services as well as scheduling for energy efficiency."*

This deliverable is not based on analytical work and no analysis will be presented. It actually defines steps and describes procedures which will be applied in following WP4 tasks in order to model and to evaluate system performance and improvements.

The description of deliverable 4.1 in the DoW is:

D4.1) Efficiency analysis methodology: In order to measure the efficiency of the resource usage within the production environment a set of parameters, i.e. performance indicators, will be defined. Furthermore, a methodology for their determination will be developed and a step-by-step procedure described. Utilising these performance indicators control parameters of the resource networks can be identified and influenced.

Deliverable D4.1 has been prepared by De Montfort University (DMU) with a significant contribution from Fraunhofer IWU and other contributions from Integrated Environmental Solutions (IES), Jakob Energy Research (JER) and IKERLAN. It comprises six chapters:

Chapter 1 – Introduction. This briefly summarises the main objectives of work package 4 as well as the T4.1 aims and work steps. In addition, it presents a holistic view of the concept of resource networks which goes beyond energy and material flows and includes personnel and information flows as well.

Chapter 2 – Demand Profiles. This characterises demand in industrial facilities mainly focusing on electricity demand, heating demand and cooling demand. It defines necessary demand characteristics which have to be obtained in order to be able to model and evaluate energy generating systems. It also emphasises the impact of energy demand profiles on equipment sizing. Moreover, it describes possible approaches for obtaining energy demand profiles including monitoring, rough-cut modelling and simulation.

Chapter 3 – Renewable Energy Systems. This focuses on technical solutions mainly related to the three industrial sectors that the REEMAIN project will demonstrate. The most promising innovative technologies, identified in WP3 (T3.1) have been selected and evaluated. These are photovoltaics, solar thermal collectors, solar concentrators, hot water storage, lithium-ion batteries, solar cooling, combined heating, power and cooling (CHPC), and organic Rankine cycle (ORC). The particular emphasis is on the basic modelling techniques for each of them as well as on required inputs and simulation models which describe the physical behaviour of particular technologies.

Chapter 4 – Renewable Energy Systems Coupling. This shows the potential configuration of the systems described in Chapter 3 as a part of larger system. The main strategy is extending the energy generating equipment with storage technologies in order to provide better match between energy supply and demand and to improve a overall system efficiency.

Chapter 5 – Modelling Tools. This describes the main features and characteristics of modelling tools that we plan to use in WP4. Tools are subdivided into four groups: supply side (system) modelling tools (such as EnergyPlus and TRNSYS), tools for developing new component models (such as Matlab and EES), demand side (plant) modelling tools (such as IES-VE rough-cut modelling, Siemens Plant Simulation), and data exchange/processing tools (such as jEPlus and Python).

Chapter 6 – Modelling Approach. This presents preliminary thoughts on a modelling approach which we plan to apply in the remaining work package 4 tasks. The main aim of modelling is to identify the most suitable set of advanced energy generating systems (including renewable technology), described in Chapters 3 and 4, which can partially or fully replace conventional energy generating systems in response to industrial facility energy demands, including heating, cooling and electricity, within a particular climate conditions.

1.1 Resource Networks

The fundamental aim of the Resource Networks Methodology is to achieve a symbiosis of renewable energy applications, efficient technologies and innovative approaches to production organisation. In the following, an extract from an Elsevier published research paper [1] discusses the motivation behind and the general concept of the methodology.

> *The integration of renewable energy into the factory environment raises difficult questions regarding the use of energy. Such renewable energy sources are versatile and usually insufficient*

to cover the entire energy demand of a factory at all times. Their supply profiles can rarely be predicted correctly and they seldom conform to the demand profiles. In general, there is a time offset between the production and the consumption of energy.

As of 2013, approx. 39.6 % of the installed power capacity in the EU stems from renewable energy sources [2]*. This is a considerably larger share than the share of renewable energy in the gross final energy consumption (14.1 % in 2012* [3]*). Hence, one of the most important problems to be solved is the storage problem* [4]*. Although this necessity is well known and many researchers are examining and developing new solutions, many of these are still not suitable for extensive industrial application. Multi storage systems are an approach intended to solve this issue* [5]*. They shall allow for the optimal integration of renewable sources which makes them another focus for activities by academics and companies (e.g.* [6]*). This work aims to find solutions for structuring, dimensioning, and controlling multiple volatile energy sources utilising storages.*

Most research up until now neglected the fact that the energy supply systems always interact with the demand side. However, making use of the levers provided by the consumers may enhance the flexibility of hybrid supply systems. Demand response is an approach which takes this possibility into consideration [7]*. The basic principle is that a system for load management may shut down or turn on energy drains (machines) depending on the highest Economic Value Added. Using this approach, factories can act as drains for surplus energy in the grid or reduce their own load on the grid in times of high demand, and get paid for it by the grid operator.*

The Smart Grid is one of the few integrative approaches, which makes use of combined supply and demand side management [8]*,* [9]*. Its goal is to ensure the availability of energy by monitoring and controlling sources, storages, and consumers (drains) on a regional or trans-regional level. Smart Grids can be broken down into Micro Grids. The latter act as autonomous entities and are localised groups of energy generation units, storages, and consumers. They are connected to local grids but can also operate autarkic.*

The idea of Micro Grids initiated the Resource Networks concept, which provides guidance on how to describe and control decentralised subsystems within factories. It allows for breaking down the complex problem of managing energy optimally for an entire factory into smaller, easier problems. Resource Networks consist of different pieces of equipment and facilities (elements) which can be characterised using substitute models (subsection 1.1.1). Each of these is an autarkic subsystem of the factory which provides the operator with flexibility on different levels (subsection 1.1.2). Hence, not only planning but also control strategies can be used to optimise the operation of these networks and to retain the production efficiency of the whole factory (subsection 1.1.3).

1.1.1 ELEMENTS OF RESOURCE NETWORKS

In order to effectively implement the idea of Resource Networks, coping with the complexity of reality is a prime concern. The definition and utilisation of substitute models describing the most important attributes of the actual equipment, facilities, etc. is an established approach to solve this issue [10], [11], [12], [13]. *Accordingly, the Resource Networks concept makes use of models for the description of its elements. These are derived from the various flows which can be observed in a production environment. Following* [14] *these are the flow of material, energy, information, personnel, and capital. The latter, however, is disregarded hereafter as costs and profits/value-creation always need to be contemplated, regardless of the introduction of the Resource Networks concept. Figure 1 depicts an overview of the most important elements subsumed in these flow categories along with exemplary features used in corresponding substitute models as part of the Resource Networks concept.*

It should be noted that these categories focus only on certain aspects of a production environment, similar to the different views of ARIS [15]. *Hence, adequate descriptions of actual work systems require a combination of these substitute models. For instance, a machine tool can be modelled as a combination of a piece of production equipment, an energy source, and a set of energy data. This division of information is intentional as the Resource Networks concept aims to simplify large, complex problems into multiple smaller problems. This will be elaborated in subsection 1.1.3.*

The material flow and associated elements are concerned with all equipment and facilities which directly (e.g. machine tools) or indirectly (e.g. tool supply systems) advance the finalisation of products or realise logistics tasks between individual production steps (e.g. buffers or fork lifts). Thus, all descriptive features focus on aspects that influence the progress of production.

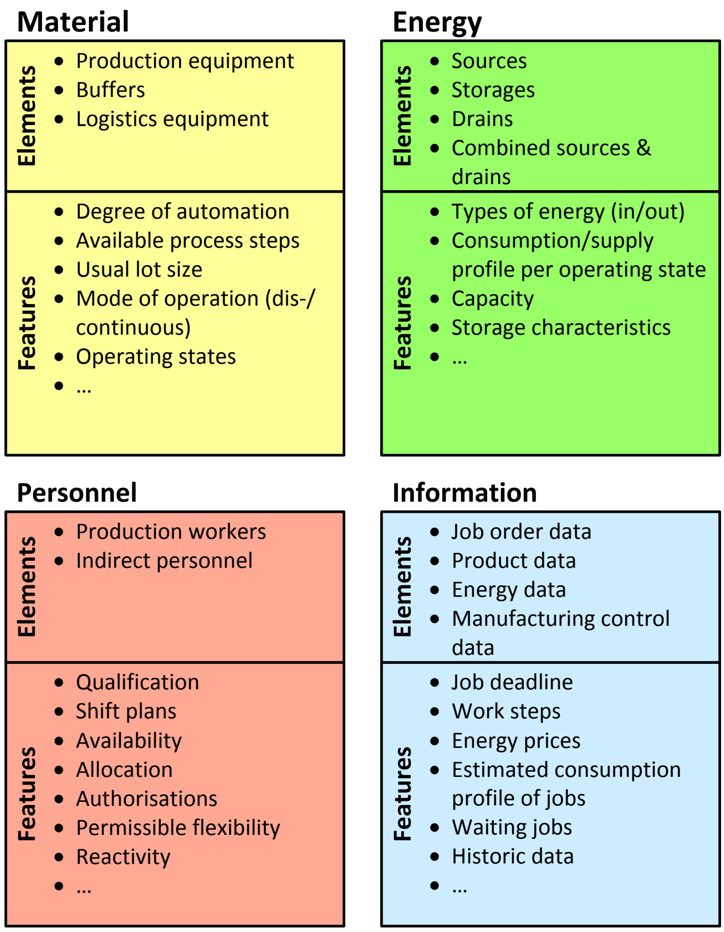

FIGURE 1 ELEMENTS OF THE VARIOUS FLOWS IN A PRODUCTION ENVIRONMENT [1]

Considering the flow of energy, there are basically only sources (e.g. water boiler) and drains (e.g. machine tools), combinations thereof (e.g. air compressors using electricity to provide compressed air), and storages (e.g. fly wheel storages). This disregards the factory internal supply networks which are expected to be optimised technically to complement the Resource Networks concept. The substitute models used in this category are meant to describe the input and output of all production, logistics, and infrastructure equipment concerning all types of energy in all situations.

Personnel are just as important for a production operation. The corresponding substitute models aim to describe workers who interact directly with the material flow or are responsible for mandatory maintenance tasks. Their description is a requirement for planning the deployment of the labour force.

In order to effectively plan and control a production site, a multitude of data providing information on the jobs to be finished, the products to be produced, etc. has to be taken into account. Accordingly, the models of information elements define the most important specifics which are necessary for the Resource Networks concept.

1.1.2 DEGREES OF FLEXIBILITY

Organising the elements of a factory making use of the Resource Networks concept provides plant designers and managers with new opportunities to reach a higher level of renewable energy integration. The degree of flexibility of each network is related to different levels of energy supply and consumption, i.e. the supply level, the production level, and the infrastructure level. This is depicted in Figure 2.

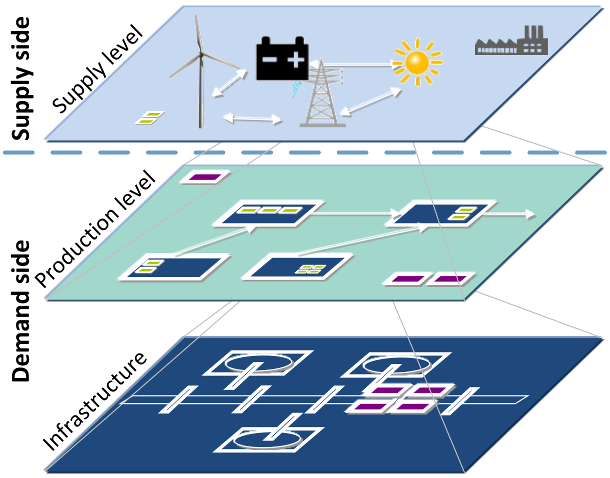

FIGURE 2 LEVELS OF FLEXIBILITY IN A FACTORY [1]

Keeping in mind that most renewable energy sources have a specific, non-static energy supply profile, all energy sources in a factory need to be planned carefully and possibly implemented redundantly so they can (partly) substitute each other. While this imposes certain restrictions on production control tasks, it also allows for flexible control on the energy supply level of a Resource Network. More precisely, it becomes possible to decide which source should be used at which time and for how long. In terms of factory planning, this means that the dimensioning of the energy supply needs to be oversized to enable ad-hoc shifting between energy sources in case the availability of renewable energy changes or economic aspects advocate it. In light of the resulting energy supply mix of the production system, the most important criteria must be full availability of energy whenever needed for production tasks. Moreover, the production output should never decrease due to a lack of supplied energy. Nevertheless, the Resource Networks concept also incorporates flexibility on the demand side which may shift the energy demand whenever the supply side is not able to cope.

Idle times of equipment and facilities can be found in any factory during its operation. They are usually caused by breaks in the shift or job schedule, or by maintenance. During this time machines are running on full power in most companies but do not produce anything. The Resource Networks concept tries to improve upon this on the production level of flexibility by implementing intelligent management routines for the material and information flows. For this purpose, advanced equipment control solutions (e.g. eniMES [16]*) are used to exert control over the operating states* *of system elements and, thus, the material flow. These are used to realise adjustments to the results of conventional production planning and control (PPC) for deploying equipment and personnel according to the availability of renewable energy sources. Through this influence on the demand side, buffer times and material buffers can be used to "store energy in products" by producing in advance of the job schedule or to reduce the system's overall consumption by delaying work tasks while maintaining high productivity.*

Another suitable lever for influencing the demand side can be found on the infrastructure level which is concerned with realising the supply of process media, such as compressed air, chilled water, hot water etc. While these media are required anyway, storing most of them is reasonably easy. Hence, temporarily shutting down their suppliers provides opportunities for reducing the actual energy demand of a Resource Network. Similarly, excess energy can be used to prospectively generate these media for later use. Additional storages can be implemented on this level to increase the attainable flexibility. Energy recuperation systems may also be employed to make use of excess energy which is usually emitted into the environment without any further use (e.g. heat loss). This allows for making links between unused energy sources and existing drains. Depending on the mode of operation and the quantity of available and required energy of both, it may be possible to replace or downsize existing supply equipment (e.g. hot water boiler).

1.1.3 REALISING DECENTRALISED FACTORY OPERATION

To break down a complex problem into multiple smaller problems, the first step of the here-described concept is to define suitable Resource Networks in a factory using the substitute models introduced in subsection 1.1.1. These may overlap wherever suitable to ensure that each network is functional by itself. This is an important aspect, considering that a cogeneration unit, for instance, might provide electricity to one set of equipment while providing heat for another one. Figure 3 exemplifies how a simplified production system can be broken down into three Resource Networks (RN1-RN3). All of the latter include the electricity grid which does not necessarily mean that it will be relied on at all times but might just as well act as a fall back for unforeseeable situations.

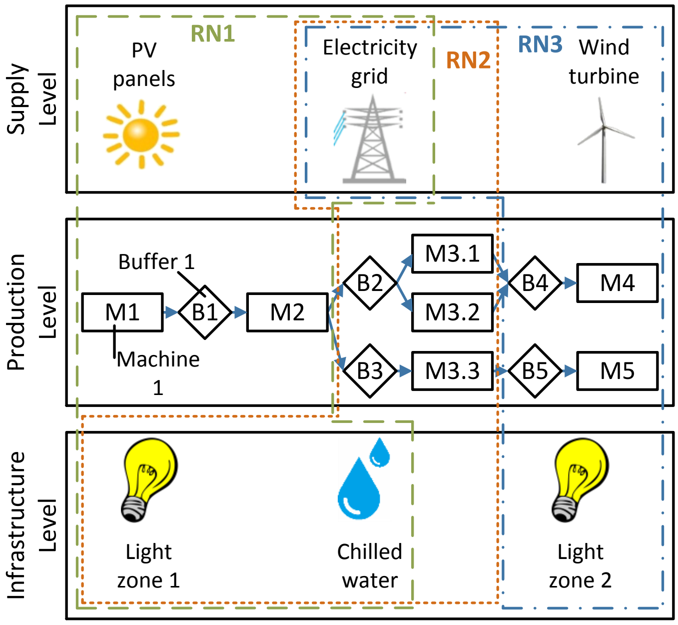

FIGURE 3 EXEMPLARY RESOURCE NETWORKS IN A SIMPLIFIED PRODUCTION SYSTEM [1]

Individual elements of the regarded production system are described using multiple substitute models to include all their important features. However, the networks are defined with no consideration of the flow categories and, thus, should include all the categories from Figure 1 with the possible exception of personnel. Furthermore, all input data required for completely describing the various elements needs to be acquired and made available for later processing. A suitable solution would be a linked data representation, such as described as part of the "Linked Factory" concept [17].

Once this step has been completed, the gathered information can be used to plan the introduction of new renewable energy sources or to devise mechanisms which help to control the networks in a way they cope with the volatile energy supply. The earlier possibility is concerned with making use of hitherto wasted energy emissions, e.g. use excess heat for pre-heating boiler water, or substituting conventional with renewable energy sources, e.g. use geothermal cooling instead of electrically powered refrigeration. Solutions, which are planned once and need no further control mechanisms, can be considered static as they do not require any further flexibility.

More dynamic strategies can be applied throughout the different levels a Resource Network covers. A prime example is the possibility to dynamically shifting between different energy suppliers on the supply side. For this purpose, the supply profiles of the corresponding energy sources elements have to be analysed. Due to the fact, that the overarching objective is the integration of renewable energies, the profile of one such renewable source will pose as the basis for decision making. It has to be compared to the aggregated profile of all consumers of the network in order to identify shortages. These can then be remedied by selectively shifting to other *sources which are less dependent on external influences like the weather or by making use of available energy storage equipment.*

This strategy can also be reversed by adjusting the production process, i.e. the material flow, in order to change the overall consumption profile. Again, the profiles of all energy drains and sources elements within the network will have to be aggregated in order to identify discrepancies. The resulting information is used to determine which load should be moved, i.e. which machines should operate at another time. Possible solutions for shifting demand, which will not diminish the output of the Resource Network, may be found through the analysis of the material flow elements along with other information flow elements (e.g. job data). This is possible if buffer times exist in the job schedule or material buffers exist between individual work systems in the factory. Once a feasible alternative has been found, the personnel deployment may need to be checked, too.

These explanations show that the flexibility on the production level is associated with a considerable complexity despite a step-by-step solution process. Infrastructure can prove somewhat simpler as it does not immediately influence the value creation of a production system. Accordingly, the process for the infrastructure level identifies discrepancies between the demand and supply profiles (see above) and selects elements (combined drains and sources) which may cease operation for some time making use of installed storages (e.g. for compressed air). Thus, load can be moved to a time where surplus energy is available to produce process media in advance or to lower the overall demand.

The above approaches may also be combined, if both the supply and demand side should be manipulated. This requires a more complex, iterative solution process which identifies discrepancies and determines adjustments to the management of energy sources, the flow of production, and the deployment of personnel. Naturally, all flows in a production environment have to be observed to generate feasible solutions.

In conclusion, the concept of Resource Networks is meant to provide means for planning and controlling production systems which make explicit use of decentralised, on-site renewable energy sources. For this purpose, it breaks down a large, complex problem into multiple smaller and simpler ones by creating virtual networks, which are principally self-sufficient, spanning both the supply and the demand side and considering all relevant types of energy or media flows (resources).

2. Demand Profiles

The main aim of obtaining a facility's energy demand profiles is to be able to model the performance of primary systems, including renewable energy systems (RES), installed at the source side. Energy demand profiles are also needed in order to properly size primary systems. Primary systems have to be properly sized and capable of providing sufficient energy to respond to demand profiles at any time since the stability of the process used by the industrial facility cannot be compromised.

REEMAIN is mainly focused on the integration of renewable energy systems (RES) as a source of energy in industrial facilities and as a means of reducing a facility's carbon footprint. At the facility levels, energy demand profiles can be presented in a simplified way and with fewer parameters than at the process level. The number of parameters is mainly defined by the characteristics of proposed RES technologies since required parameters are usually necessary inputs for RES modelling.

Various types of energy can be used in industrial facilities in order to support different production processes as well as technical building services (TBS). For simplicity, it can be assumed that the energy is provided from centralised spaces (e.g. plant rooms) where the main energy meters are located. Three of the most common types of energy carrier supplied to industrial facilities are:

1. Electricity
2. Heat
3. Cooling energy (coolth)

The performance evaluation of primary systems, when responding to a facility's energy demands, is affected by the characteristics of energy demand and, in some cases, exterior environmental conditions. These are the main reasons for requiring annual energy demand profiles with no less than hourly resolution. Higher resolutions of energy demand data (seconds or minutes) can be aggregated in 10-minute timesteps (building/systems simulation tools default simulation timestep), 15-minute timesteps (typical in Germany) or half-hourly (typical in the UK).

2.1 Characteristics Of Demands

The demand of electricity and other energy carrying or process media in a factory is naturally highly influenced by the use of production equipment. The corresponding characteristics depend on the physics of the energy transmission, the actual flow of energy and the level of flexibility (depicted in Figure 2) for which the demand is considered. Figure 4 depicts the flow between the different levels of flexibility and gives examples of the actual media being exchanged between the levels. The difference can further be illustrated by differentiating the type of energy demand into primary, secondary and tertiary energy (see Table 1)

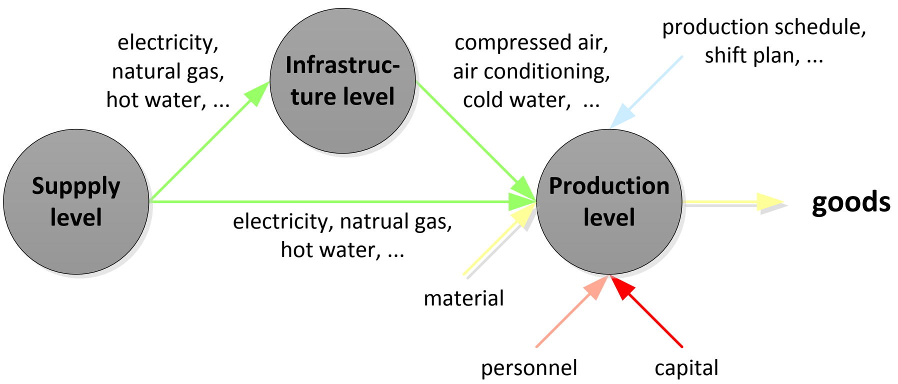

FIGURE 4 FLOWS OF PRODUCTION REQUIREMENTS IN A RESOURCE NETWORK [18]

TABLE 1 TYPES OF ENERGY DEMAND (ACC. TO [19], P. 23)

Type	Primary	Secondary	Tertiary
Description	*Energy as it occurs in nature* [...].	Form of energy which has been extracted and transformed from primary energy to be useful to humans.	Form of energy which is of immediate use to humans.
Examples	*coal, oil, natural gas, uranium* [, sunlight, wind, ...]	*electricity, refined petroleum products,* [...] *processed natural gas* [...] [, heated water from solar collector, cooled water from geothermic installation, ...]	*warmth, motion, mechanical power, process heat*

Accordingly, the supply level provides primary and secondary energy to the infrastructure level and the production level. The infrastructure level either transforms primary energy to secondary energy or one kind of secondary energy to another kind of secondary or tertiary energy. Hence, its demand depends on the requirements of the production level and its inherent capability for storing the different types of transformed energy during operation. This usually causes the demand profile to be more levelled than in the production level.

The demand of the infrastructure level and the production level is a superposition of the demand of the corresponding pieces of equipment. Each of those can be modelled (and approximated) using a finite number of operating states, which are associated with a certain consumption (or demand) profile. The current operating state of a piece of equipment depends on its necessity for the production process (direct or indirect), its controllers and the production organisation. Naturally, any machine will be operational when the production process calls for it. However, the actual production program on the machine can differ according to the processed job order, i.e. production demand, and so can the operating state. Whenever no production is planned, the machine will enter an idle state but may as well be turned off (partially). This depends on the controller programming, the machine complexity, the production schedule (for the machine), the machine operator and the quality demands for machine operation, amongst others.

A demand profile for a given period of any piece of equipment can be modelled as a sequence of operating states. The demand of an entire level is the superposition of multiple individual pieces of equipment requiring the same kind of energy or process media. The actual sequences, in turn, follow certain characteristics, which have been detailed below.

The demand of the production level is influenced by the production schedules, plans and equipment. In general, machine tools have high baseline consumption and the actual processing amounts for little consumption (usually well below 50 %). The actual consumption profile during a processing cycle of such machines is signified by a multitude of short, positive and negative spikes which are the result of the tool getting in touch with the material to be processed (positive) and the de-/acceleration of different axis (positive and negative). These are intermitted by idle times for tool changes, pauses or unplanned times. The profiles of industrial robots are usually comparable to those of machine tools; however, the baseline consumption is much lower, if only the robot and no other associated equipment (e.g. welding unit) are regarded. The consumption of process technology or other (semi-)continuously working equipment is generally more stable and follows longer cycles. Logistics equipment either follows discontinuous cycles (comparable to machine tools) or operates continuously, depending on their type.

In contrast, some, if not most, infrastructure equipment is working around the clock and not only during production time, unless prolonged unscheduled periods (e.g. weekend) are entered. Another influence is the weather and time of year. The demand of lighting and air conditioning equipment, for instance, is dependent on such environmental influences.

Considering the different types of energy or process media, the arising demand needs to be met at once, over a short time or over a long time. This is explained and exemplified in Table 2. The physics associated with the use of energy is the reason for the differences in demand response time for the different types of energy. They along with the possibility for storage also influence how the supply needs to be handled. For instance, electricity with no intermittent storage has to be supplied as needed; a compressed air system with an air reservoir needs to be refilled when pressure drops too much; cold/warm water systems have to be operated continuously (possibly with varying flow rates); and a climate control unit has to be operated according to external, environmental (weather, climate, …) and internal (exhaust heat, building insulation, …) influences. This causes the resulting demand profile to be more or less levelled.

TABLE 2 DEMAND RESPONSE TIME IN THE PRODUCTION LEVEL

Type	**At once**	**Over a short time**	**Over a long time**
Description	demand for energy of process steps which transform one kind of energy or media into another	demand for energy of process steps which includes some form of potential equalisation and allows for little latency	demand for energy which is generally required to execute the process
Example 1	electricity which is transformed in a motor into mechanical power	cooling water which collects heat from a welding gun to avoid overheating	suction which removes soot and exhaust gases

Example 2	compressed air which powers a translational or rotational movement	natural gas which is burned to heat an oven	climate conditioning which allows for the operation of high precision machine tools

One last thing to consider when discussing the characteristics of demand is the efficiency level. Each transformation of kind of energy to another will result in losses. Accordingly, the actual amount of tertiary energy necessary for production is only a fraction of the primary energy required. Accordingly, transformations should be kept to a minimum while their efficiency is maximised. Furthermore, each point of transformation can potentially be a lever for decoupling the demand of primary, secondary or tertiary energy (although a proportionality regarding the absolute amounts will remain in place).

2.2 Electricity Demand

Electricity demand can be defined according to the nominal power rating of the energy using equipment, expressed in units of power (Watts). The **design level** is the sum of the nominal power rating of all installed electrical equipment in the facility. The **normalised consumption profile** is obtained by dividing actual electricity consumption by the design level. The values of normalised consumption profile are between 0 and 1 with a maximum timestep of 1 hour and minimum timestep of 1 minute. An example of normalised consumption profile and a facility's electrical equipment design level can be seen in Figure 5. If suitable, more than one electricity demand profile could be created for a single facility. This is mainly in cases where demand profiles are obtained from multiple electricity sub-meters.

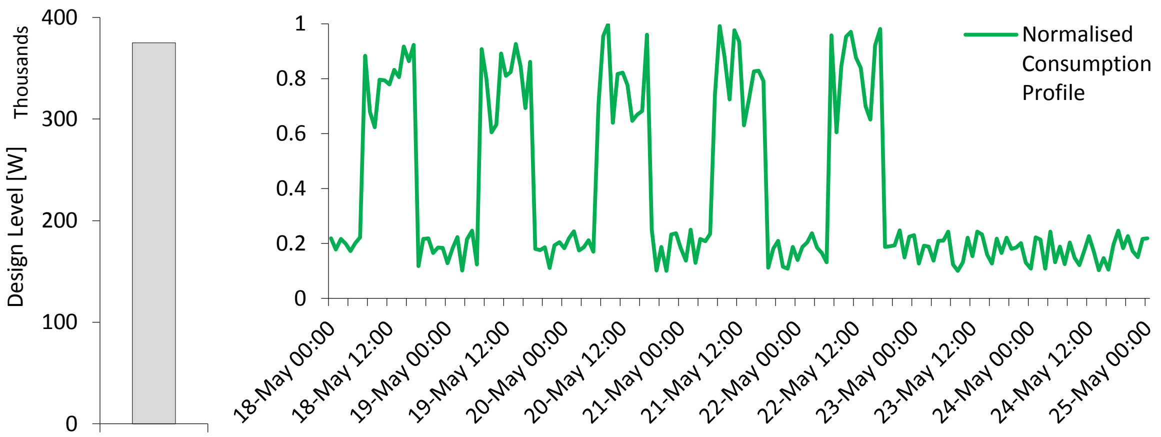

FIGURE 5 EXAMPLE OF DESIGN LEVEL AND NORMALISED CONSUMPTION PROFILE (ONE WEEK)

2.3 Heating Energy Demand

Heating energy is often required in industrial facilities for multiple purposes. In some cases, heating energy is directly consumed by a production process while sometimes its only task is to support a process. In addition, heating energy is often required to control indoor environmental conditions. The source of heating energy can be divided based on the place where energy is generated, and into two categories: centralised sources or local sources. Local sources often generate heating energy to be consumed by a production process itself, such as baking or furnaces, and in most cases the energy is a product of the direct combustion of fuel. Although two of REEMAIN's three demo cases utilise such local heating energy sources, they are out of scope of this methodology since it is very complex to replace them with centralised sources (in particular RES) without having significant implications for production processes.

Centralised sources produce heat to cover demand at locations (sinks) that are remote from the source. The energy is transferred from source to sinks via heat transfer media. The most common heat transfer media are hot water and steam. Heat demand should be specified by demand profile [W] with at least hourly timestep resolution (Figure 6). The annual heating demand profile is preferable since the performance of several heat generating technologies proposed by REEMAIN depends on exterior environmental conditions. In addition to heating demand, operating conditions have to be defined. The required operating conditions differ based on the type of heat transfer medium.

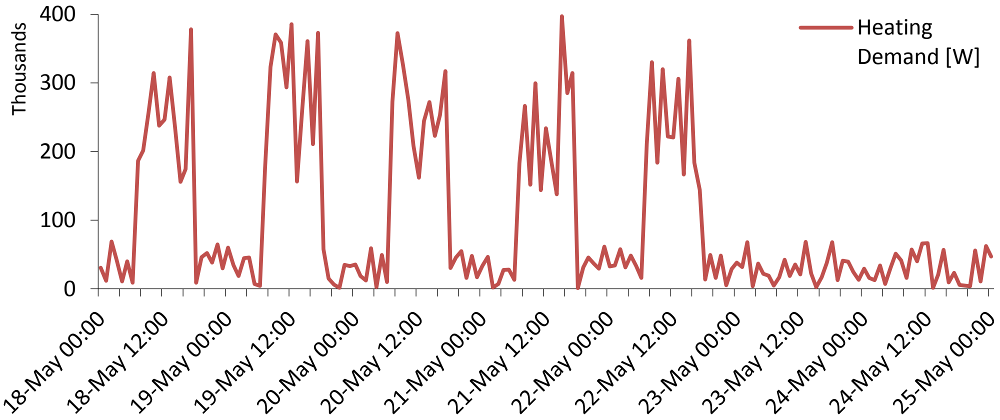

FIGURE 6 EXAMPLE OF HEATING ENERGY DEMAND PROFILE (ONE WEEK)

2.3.1 HEATING ENERGY DEMAND – HOT WATER

In cases where hot water is used to deliver heating energy from sources to sinks, up to three additional parameters have to be obtained. These are:

1. Supply hot water temperature
2. Peak (design) flow rate or design temperature drop
3. Flow rate fraction (FRF) profile (optional)

The schematic representation of a simplified supply/demand loop connection is presented in Figure 7. The demand side can be specified as a range of individual demands arranged in series, parallel or both. However, if all of them are supplied from the same source (or a range of sources) and a supply water temperature is equal, the total heating energy demand can be derived from the individual heating energy demands by simply aggregating them all.

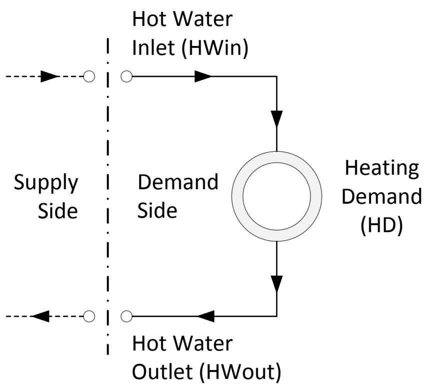

FIGURE 7 HOT WATER SUPPLY/DEMAND LOOP CONNECTION

Equation 1 is used to calculate unknown demand loop parameters for a peak (design) conditions.

$$HD_{max} = \rho \cdot \dot{V}_{max} \cdot c_p \cdot \Delta t_{design} \quad \text{EQUATION 1}$$

where:

HD_{max} [W] is a nominal (designed) capacity,

ρ [kg/m^3] is a hot water density,

$\dot{V}_{max}$ [m^3/s] is a peak volume flow rate,

c_p [J/kg-K] is the specific heat capacity of water,

Δt_{design} [°C] is a hot water design temperature drop.

Design temperature drop is a difference between a supply hot water temperature (t_{HWin}) and a return hot water temperature (t_{HWout}). Usually, the known design parameters are HD_{max} , t_{HWin} and Δt_{design}. Knowing these three values, the $\dot{V}_{max}$ can be calculated. Equation 2 shows heating demand calculations during part load operation

$$HD = \rho \cdot FRF \cdot \dot{V}_{max} \cdot c_p \cdot \Delta t \quad \text{EQUATION 2}$$

where:

HD [W] is a heating demand,

FRF [-] is a flow rate fraction which is a ratio of a part load volume flow rate ($\dot{V}$) and a peak volume flow rate ($\dot{V}_{max}$), and

Δt [°C] is a hot water part load temperature drop.

The part load operation can be controlled in two ways:

a) By keeping a fixed volume flow rate ($FRF = 1$) while modulating a hot water temperature drop (Δt). Part load operation hot water temperature drop in this operation mode will always be lower than designed hot water temperature drop (Δt_{design}).

b) By fixing a hot water temperature drop to a design value ($\Delta t = \Delta t_{design}$) while varying a volume flow rate ($0 \le FRF \le 1$).This is a recommended control method when a variable speed hot water pump is installed on a supply side.

The modelling complexity of a demand side is slightly increased when there is a difference in supply hot water temperatures to various heat sinks. There are three possible ways of overcoming this issue:

a) Attach heating demand loops with different supply hot water temperatures to completely separate heat energy sources (Figure 8). This results in having independent systems in which operation and hence performance, do not affect each other.

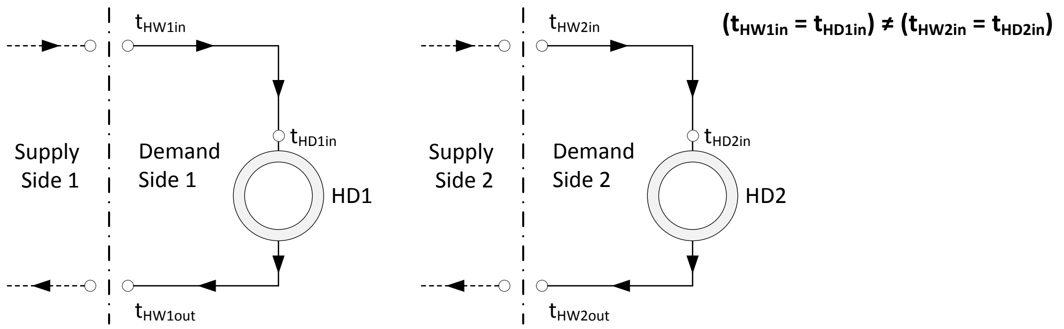

FIGURE 8 MULTIPLE SEPARATE HOT WATER SUPPLY/DEMAND LOOPS

b) Split supply hot water to supply a demand loop at a designed temperature setpoint ($t_{HWin} = t_{HD1in}$) and also to supply hot water to a demand loop operated at higher temperature setpoint (t_{HD2in}) (Figure 9). This solution requires at least two heat sources and it is not common unless minimal reheating is required. Reheating in this case is often provided by electrical immersion heaters placed in the loop (or loops) which requires a higher hot water temperature.

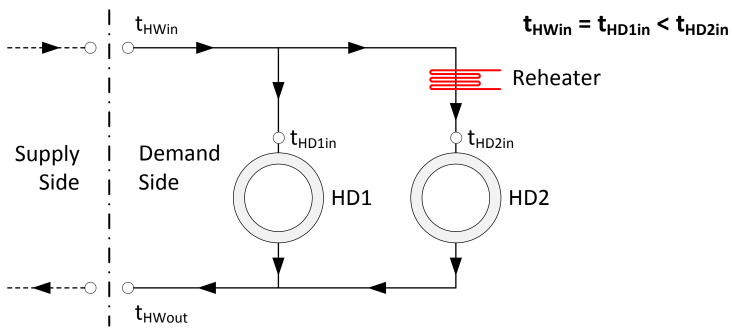

FIGURE 9 HOT WATER SUPPLY/DEMAND LOOPS WITH A REAHEATER

c) Heat supply hot water to a designed temperature setpoint ($t_{HWin} = t_{HD1in}$) of the highest temperature heat demand loop and then drop it in a heat exchanger (HX) to a level (t_{HD2in}) required by a low-temperature heat demand loop (Figure 10). This requires an additional hot water loop which connects heat exchanger and low-temperature heat sink. Some applications can be done without a heat exchanger by installing a three-port valve and a bypass in the secondary loop (secondary loop circulation pump is required as well) (HD3 in Figure 10), however controlling such installation can be more complex depending on characteristics of heating demands.

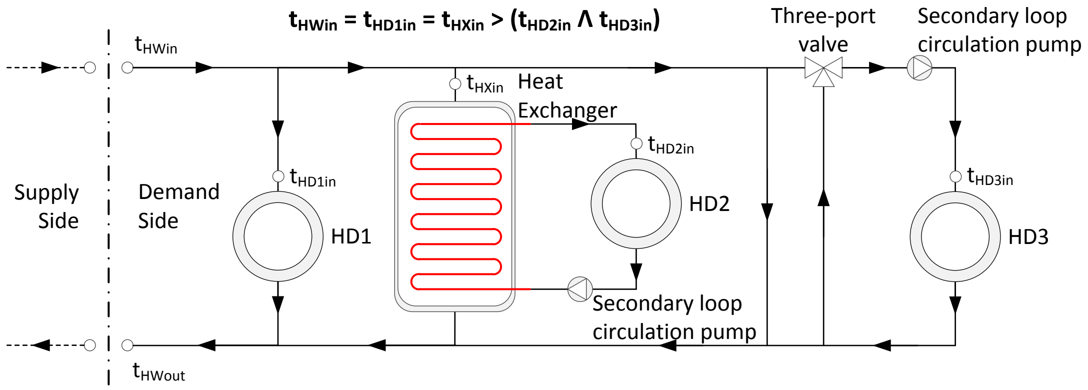

FIGURE 10 HOT WATER SUPPLY/DEMAND LOOPS WITH A HEAT EXCHANGER AND THREE-PORT VALVE

2.3.2 HEATING ENERGY DEMAND – STEAM

Three additional parameters have to be obtained in cases where steam is used to deliver heating energy from sources to sinks. These are:

1. Steam pressure
2. Steam condition: saturated or superheated
3. Condensate condition: sub-saturated water or saturated water

Steam systems can be divided into low pressure and high pressure systems. Low pressure systems operate at pressures around atmospheric pressure while high pressure systems can operate at pressures up to 27 bars [20]. If steam is saturated, then its temperature can be obtained by knowing only the system pressure. In cases where a system requires superheated steam than the temperature of the superheated steam has to be specified as well. Similar parameters have to be specified for the condensate. If it is saturated water than the system pressure is enough to obtain condensate temperature. However, if condensate is subcooled than the temperature of sub-saturated water needs to be specified. Equation 3 shows calculation of unknown demand loop parameters for peak (design) conditions

$$HD_{max} = \dot{m}_{max} \cdot \left(c_{pw}(p_s) \cdot \Delta t_{SCW} + h_e(p_s) + c_{ps}(p_s) \cdot \Delta t_{SHS}\right) \quad \text{EQUATION 3}$$

where:

HD_{max} [W] is a nominal (designed) capacity,

$\dot{m}_{max}$ [kg^3/s] is a peak steam mass flow rate,

$c_{pw}(p_s)$ [J/kg-K] is a water specific heat - function of a system pressure (p_s),

Δt_{SCW} [°C] is a difference between a temperature of a saturated water ($t_{SW}(p_s)$) and a subcooled condensate (t_{SCW}),

$\mathrm{h_e}(p_s)$ [J/kg] is an enthalpy of evaporation – a function of system pressure (p_s),

$c_{ps}(p_s)$ [J/kg-K] is a steam specific heat – a function of system pressure (p_s),

Δt_{SHS} [°C] is the difference between the temperature of the superheated steam (t_{SHS}) and the saturated steam ($t_{SS}(p_s)$).

Figure 11 graphically represents a simplified steam supply/demand loop connection.

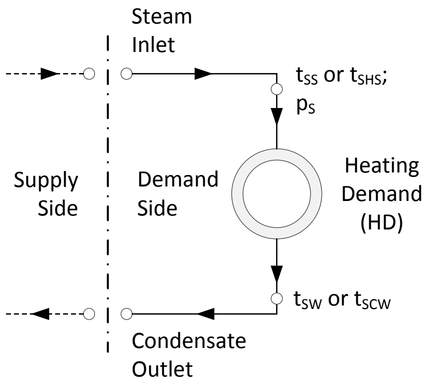

FIGURE 11 STEAM SUPPLY/DEMAND LOOP CONNECTION

If the system operates with saturated steam and saturated water then both Δt_{SCW} and Δt_{SHS} are zero while Equation 3 can be presented in simplified form (Equation 4).

$$HD_{max} = \dot{m}_{max} \cdot h_e(p_s) \quad \text{EQUATION 4}$$

Equation 3 and Equation 4 are useful to calculate the peak design steam flow rate ($\dot{m}_{max}$). Part load operation of steam systems is controlled by varying the steam mass flow rate. Equation 5 shows heating demand calculations during part load operation.

$$HD = FRF \cdot \dot{m}_{max} \cdot \left(c_{pw}(p_s) \cdot \Delta t_{SCW} + h_e(p_s) + c_{ps}(p_s) \cdot \Delta t_{SHS}\right) \quad \text{EQUATION 5}$$

where:

HD [W] is the heating demand,

FRF is the dimensionless flow rate fraction which is a ratio of part load steam mass flow rate ($\dot{m}$) and peak steam mass flow rate ($\dot{m}_{max}$). FRF is modulated between 0 and 1 in order to respond to the part load heating demand.

2.4 Cooling Energy Demand

Industrial facilities often have cooling requirements. Cooling energy can be consumed directly by a process, used to support the process or used to maintain comfortable and healthy indoor conditions for occupants. Cooling energy can be produced locally by using localised coolth generating equipment such as split systems or packaged systems. Although these types of equipment are not uncommon in industrial facilities they are out of scope of the REEMAIN project.

Centrally generated cooling energy is usually produced in a chiller, of which there are various types such as air-cooled chillers, water-cooled chillers, or absorption chillers. The latter is useful if there is a source of affordable/waste heat. The most common medium used to transport cooling energy from a source to a sink is chilled water, although brines are sometimes since their freezing point is lower than the freezing point of water.

A facility's cooling energy demand should be specified by demand profile [W] with at least hourly timestep resolution (Figure 12). The annual cooling demand profile is preferable; since the performance of several coolth generating technologies proposed by REEMAIN depends on exterior environmental conditions.

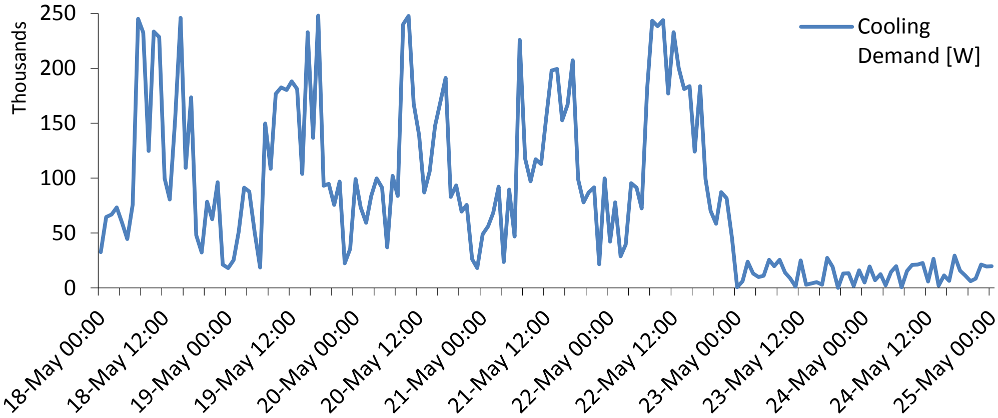

FIGURE 12 EXAMPLE OF COOLING ENERGY DEMAND PROFILE (ONE WEEK)

As with heating energy demand, chilled water loop operating conditions have to be defined in addition to a cooling energy demand. These additional conditions are:

1. Supply chilled water temperature
2. Peak (design) flow rate or design temperature rise
3. Flow rate fraction (FRF) profile (optional)

The schematic representation of a simplified supply/demand loop connection is presented in Figure 13. The demand side can be specified as a range of individual cooling demands arranged in series, parallel or both. However, if all of them are supplied from the same source and the temperature of supply chilled water is the same, they can be replaced by total cooling energy demand, which is a sum of the individual cooling energy demands.

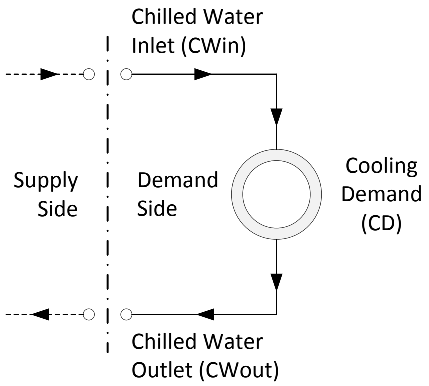

FIGURE 13 CHILLED WATER SUPPLY/DEMAND LOOP CONNECTION

Equation 6 is used to calculate unknown demand loop parameters for a peak (design) conditions.

$$CD_{max} = \rho \cdot \dot{V}_{max} \cdot c_p \cdot \Delta t_{design}$$ **EQUATION 6**

where:

CD_{max} [W] is a nominal (designed) capacity,

ρ [kg/m^3] is a chilled water density,

$\dot{V}_{max}$ [m^3/s] is a peak volume flow rate,

c_p [J/kg-K] is a water specific heat,

Δt_{design} [°C] is a chilled water design temperature rise.

Design temperature rise is a difference between a return chilled water temperature (t_{CWout}) and supply chilled water temperature (t_{CWin}). Usually known design parameters are CD_{max} , t_{CWin} and the chilled water design temperature rise. Knowing these three values, $\dot{V}_{max}$ can be calculated. Equation 7 shows cooling demand calculations during part load operation

$$CD = \rho \cdot FRF \cdot \dot{V}_{max} \cdot c_p \cdot \Delta t \quad \text{EQUATION 7}$$

where:

CD [W] is a cooling demand,

FRF is the dimensionless flow rate fraction which is a ratio of part load volume flow rate ($\dot{V}$) and peak volume flow rate ($\dot{V}_{max}$), and

Δt [°C] is a chilled water part load temperature rise.

The part load operation can be controlled in two ways:

a) By keeping the volume flow rate constant ($FRF = 1$) while varying a chilled water temperature rise (Δt). By operating in this way, the chilled water temperature rise during part load operation is always lower than the designed chilled water temperature rise (Δt_{design}).

b) By varying the volume flow rate ($0 \leq FRF \leq 1$) while the chilled water temperature rise is fixed to a design value ($\Delta t = \Delta t_{design}$). This is a suitable control mechanism when a variable speed chilled water pump drives water through the system.

There might be situations where various cooling energy demands within the same facility require different supply chilled water temperature; and this can be solved in two ways:

a) Split cooling energy demands with different supply chilled water temperature into multiple demand loops and then attach them to completely separate cooling energy sources (Figure 14). Separate systems do not affect each other operation and do not impact on each other's performance.

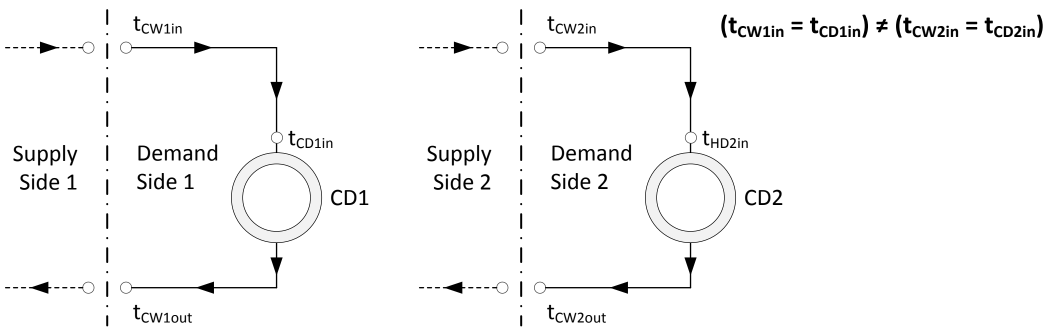

FIGURE 14 MULTIPLE SEPARATE CHILLED WATER SUPPLY/DEMAND LOOPS

b) Cool down the whole chilled water stream to the lowest required supply chilled water temperature. Cooling energy demand loops which require a higher chilled water temperature can be attached to the main demand loop via a heat exchanger or by using a three-port valve and a bypass (Figure 15). In both cases a separate chilled water loop equipped with a secondary chilled water pump is required.

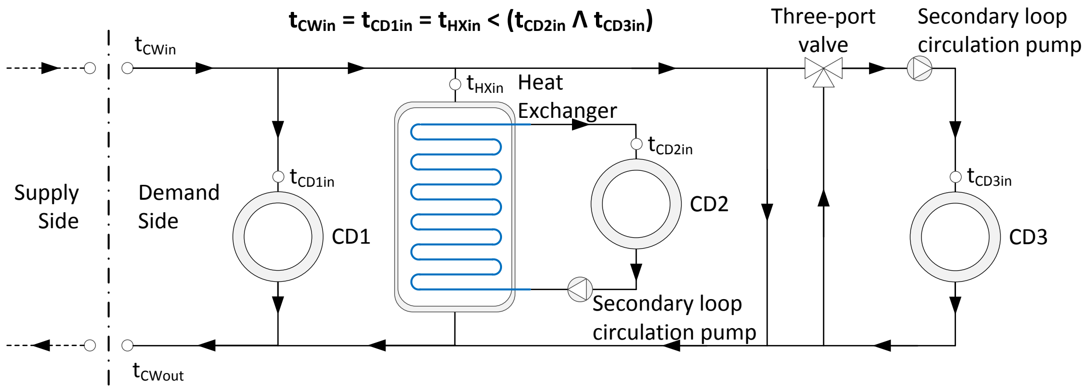

FIGURE 15 CHILLED WATER SUPPLY/DEMAND LOOPS WITH A HEAT EXCHANGER AND THREE-PORT VALVE

2.5 Impact Of Demand Profiles On Equipment Sizing

Having access to high-resolution energy demand profiles is crucial for assessing the performance of energy generating equipment, in particular when this equipment is partially or entirely based on renewable energy sources. In addition to performance evaluation, these profiles are also important for sizing the equipment. Equipment size affects both its performance and capital cost. Conventional energy generating equipment has to be sized according to the maximum energy demand since it has to produce enough energy to meet demand all the time, unconditionally. A production process cannot be compromised by lack of available energy. Quite often there is also an oversizing margin applied as well as an installation of backup facilities.

One of the REEMAIN tasks is to integrate more sustainable solutions, including renewable energy systems, into facilities' energy generating systems in order to improve efficiency, reduce CO_2 emissions, and offset energy dependence on external sources. However, this does not necessarily mean that total energy demand has to be met by integrating new energy systems. It is important to establish a balance between their renewable energy system size (i.e. cost) and operation utilisation, which is not possible without analysing high-resolution energy demand profiles.

Most of the energy generating equipment is most efficient when operated at (or close to) full load while the efficiency drops (sometimes significantly) at part load operation. Part load ratio (PLR) can be defined as a ratio between a demand at certain period of time and full load. Characteristics of part load operation can be obtained from high-resolution annual energy demand profiles. A histogram of cumulative hours as a function of PLR is useful chart which can help making equipment sizing decisions. The shape of the histogram is highly affected by number of factors such as energy consumption intensity, production operating hours, number of shifts, base load energy, consumption during unoccupied hours, to mention just a few. This can shift focus from production energy demand, which explains why it is beneficial to analyse part load operation during production hours separately.

Figure 16 shows two histograms of operating hours at different part loads during the whole year (left hand histogram) and during production hours (right hand histogram). These histograms were made with the assumption that the average energy demand during production hours is around 30% of maximum demand. This means that the system operates at full load only occasionally. Another assumption is that a production is organised in single shifts from Monday to Saturday while during unoccupied hours the system operates with an average base load of 10% of installed capacity. It can be seen from the left side histogram that an energy demand is low for most of the time; the system operates at less than 15% of available power for close to 50% of the time and this is due to long operating hours at base load during unoccupied period. This example shows why part load operation during production hours should be analysed separately, as mentioned earlier. The histogram on the right of Figure 16 shows the results of this analysis. For 50% of the production time the required energy can be generated with less than 30% of available power while for 80% of production time the required energy can be generated with less than 45% of available power. This means that if a single source is selected to respond to the demand, it will operate for most of time with a very low PLR, hence very low efficiency. Sizing an alternative source, particularly if an alternative source is based on RES, to cover maximum demand might not be the best option, since even in the best case scenario it would operate with less than half load for 80% of production time.

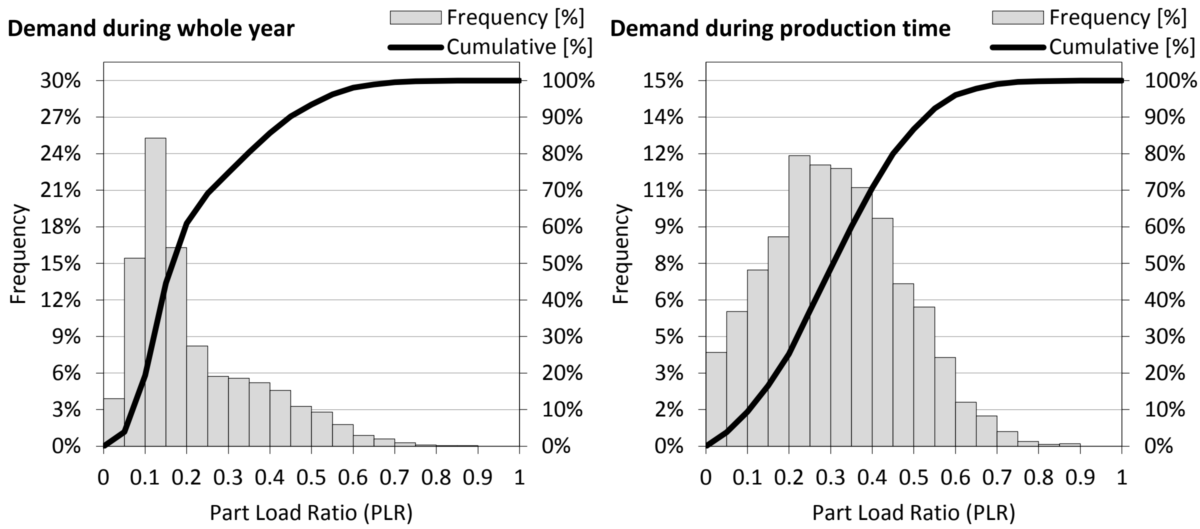

FIGURE 16 HISTOGRAM OF OPERATING HOURS AS A FUNTION OF PART LOAD RATIO FOR LOW AVERAGE DEMAND DURING PRODUCTION TIME

Figure 17 shows two histograms which were created based on the assumption that the average energy demand during production hours is around 55% of full load. It can also be seen that the left-hand histogram is dominated by consumption during unoccupied hours. The required demand during production hours can be covered with 70% of capacity for 80% of the time. It is still not justifiable to size the alternative source to cover full load. However, this demonstrates another important issue concerning the integration of multiple sources in response to the energy demand. For example it would be possible to install two sources, one with the nominal capacity of 2/3 of full load and another with the nominal capacity of 1/3 of full load. This requires the integration of advanced control mechanisms in order to control the sources' staging operation.

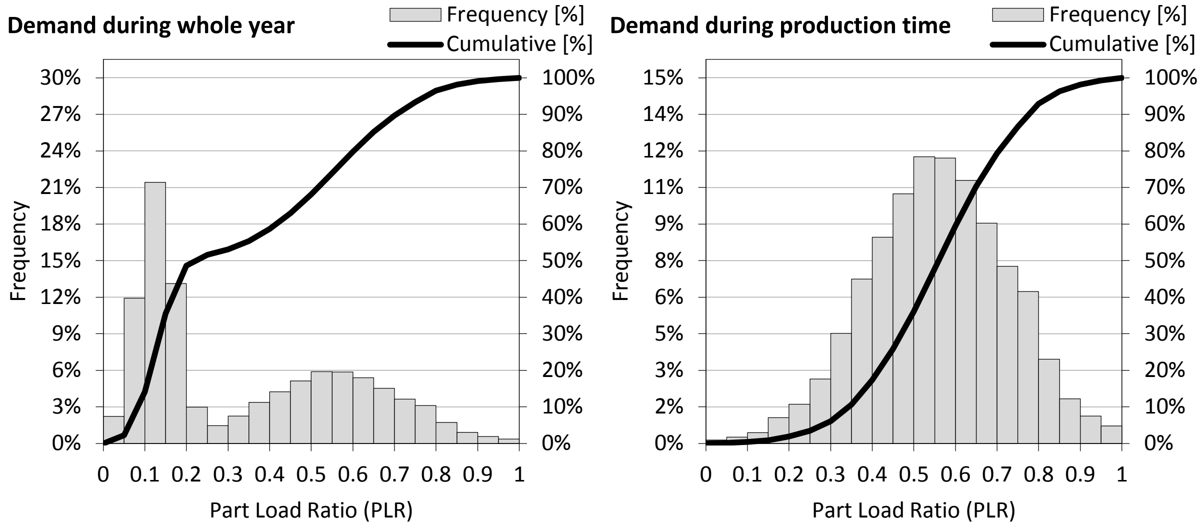

FIGURE 17 HISTOGRAM OF OPERATING HOURS AS A FUNTION OF PART LOAD RATIO FOR MEDIUM AVERAGE DEMAND DURING PRODUCTION TIME

The histograms in Figure 18 show the distribution of operating hours at certain PLR when it has been assumed that the average energy demand during production hours is around 80% of full load. It can be seen that for about 80% of the total production time the source is operated at up to 90% of installed capacity. In this situation we may consider installing an alternative energy source with a maximum capacity capable of responding to the full load. Nevertheless, source staging is also applicable to this scenario as well.

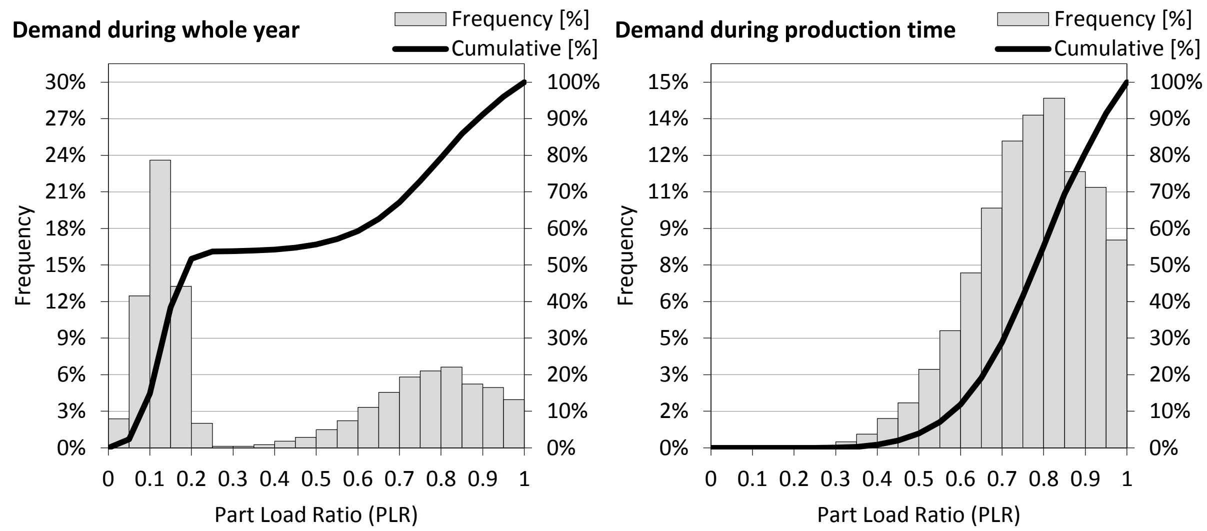

FIGURE 18 HISTOGRAM OF OPERATING HOURS AS A FUNTION OF PART LOAD RATIO FOR HIGH AVERAGE DEMAND DURING PRODUCTION TIME

2.6 Obtaining Demand Profiles

The energy demand profiles required for efficiency analysis within the scope of REEMAIN can be obtained in several ways. The detailed data can be obtained by monitoring, applying rough-cut methodology, simulating a process in specialised software, or combining two or more of these methods.

Demand profiles obtained by monitoring provide the most accurate evidence of facility consumption. Various operational conditions can be monitored (and controlled) by using digital systems such as a SCADA (Supervisory Control and Data Acquisition) system or a BMS (Building Management System). If all necessary sensors and meters are in place, automatic data collection and processing can lead to the creation of the required energy demand profiles. In some cases historical data will be available (i.e. data collected over a longer period of time) which gives additional understanding of facility operation. Much useful knowledge can be derived by having an access to such data, for example periods of a year with high/low energy demand, typical weekly operational profiles, maintenance periods, etc. Unfortunately many facilities, including two of the three REEMAIN industry partners, do not have an automatic data acquisition system. This is for various reasons such as cost and complexity. Installation of data acquisition equipment requires careful planning which usually starts by screening KPIs. REEMAIN's deliverable D.2.1 presented a systematic approach to conducting a review of currently used KPIs in facilities and identifying additional KPIs which have to be implemented in order to gather missing data. The design and development of the data acquisition architecture will be covered in REEMAIN's deliverable D.2.2.

The absence of an automatic data acquisition system makes obtaining energy demand profiles more complex. Industrial facilities often associate energy consumption with utility bills, with the only available information about energy performance being based on monthly utility bills. In extreme cases only annual energy consumption is provided. These low resolution data are not particularly useful in analysis of hourly operation of RES. However, REEMAIN's Task 3.3 (Deliverable D.3.3) developed a rough-cut approach which allows an approximation of a facility's energy use to be made. The rough-cut approach outlines a methodology for developing more detailed energy consumption profiles (preferably at hourly intervals or less) within a facility. The rough-cut approach starts with the assumption that a user has access to energy consumption data from a range of energy meters with low resolution frequency (monthly or annual). Rough-cut energy demand profiles are generated from standardised profiles which can be refined by a user based on additional available information or guided by a set of predefined questions about the facility's operations.

Another alternative is the use of simulation software. One basic assumption when following this approach is that the energy demand of production systems, as elaborated in section 2.1, depends on a number of factors, most prominently the shift schedule and the production plan. Accordingly, its behaviour can be approximated using tools which simulate the production process with all its stochastic influences. Siemens Tecnomatix Plant Simulation is a discrete event simulation software which is intended for this purpose. Recent developments by the software vendor and third parties allow for the simulation of energy consumption as well as, in some cases, supply. For this purpose, simulation objects are assigned specific energy-related operating states, which determine the consumption profile while the operating state is active. These can be variable over time but more commonly are static (i.e. average consumption in an operating state).

Fraunhofer IWU developed one such third-party solution, which is called eniBRIC [21]. It allows for parameterising each material flow object with as many operating states (with a static consumption profile) as the real machine or piece of equipment has. The simulation module is also used to model infrastructure equipment as well as other energy or media suppliers, allowing for a holistic study of production systems including all pieces of equipment on the supply and demand side.

During a simulation run, the individual model elements follow a sequence of operating states which derives from the progress of simulation (i.e. shift schedules, machine failures, work order, work progress, etc.). The information on the operating states is logged, accumulated and used to create demand profiles for each considered kind of energy carrier or process medium. Hence, it is possible to create numerous different profiles for a given production systems by using appropriate cumulative distribution functions (CDF), measured or approximated consumption data of equipment and multiple random number streams (responsible for creating stochastic events according to the CDF).

3. Renewable Energy Systems

Factory energy demand can be met by a range of different energy technologies. One of the main goals of the REEMAIN project is to help manufacturing industry to adopt more sustainable and energy efficient technologies and to integrate them within their processes. The main focus is on technological solutions related to the three industrial sectors that the REEMAIN project is interested in. Different renewable energy systems (e.g. solar concentrators for process heat, photovoltaic, wind turbines, etc.), storage technologies (e.g. thermal, electricity, etc.) and waste recovery solutions (e.g. organic Rankine cycle, heat exchanger, etc.) have been selected and evaluated. The in-depth screening of available technologies has been done in work package 3, in particular in Task 3.1. The identified technologies have been described in deliverable D3.1 which covers the basic characteristics of these technologies such as inputs, outputs, advantages, cost, etc. The descriptions of each technology have been followed by a comparison and ranking in order to identify the most suitable ones to be applied in REEMAIN's three industrial sectors. A SWOT analysis, including economic and environmental factors, has been used for the assessment of screened energy technologies. SWOT stands for:

- Strengths (characteristics of the technology that give it an advantage over others),
- Weaknesses (characteristics that place the technology at a disadvantage relative to others),
- Opportunities (elements that the technology could exploit to its advantage), and
- Threats (elements in the environment that could cause trouble for the technology).

The SWOT analysis identified the most promising innovative technologies which can potentially be integrated and demonstrated at the REEMAIN demonstration factories. These are:

1. Photovoltaics
2. Solar thermal collectors
3. Solar concentrators
4. Hot water storage
5. Lithium-ion batteries
6. Solar cooling system
7. Combined heating, power and cooling (CHPC)
8. Organic Rankine Cycle (ORC)

Although each of these technologies has been briefly described in deliverable D3.1, the following sections will present the basic modelling techniques for each of them. The particular emphasis will be on required inputs as well as on simulation models which describe the behaviour of particular technologies.

3.1 Photovoltaics (PV)

Photovoltaic technology converts the solar energy into direct current (DC) electricity. DC electricity is generated in PV cells which are usually made of semi-conductor material. PV cells are grouped together into PV panels. Inverters attached to PV panels convert DC electricity to alternating current (AC) electricity.

The electrical power produced by PV panels can be determined by using various models developed over last few decades. Models differ in complexity and the number of input parameters required. Some of them are more detailed and are often slightly more accurate than simplified models. Popular PV models are the equivalent one-diode model, also known as the TRNSYS PV model [22], and the Sandia PV performance model [23]. Both models use empirical relationships to predict PV operating performance based on many environmental variables. The simplest model for predicting PV energy production is based on user-specified panel efficiency (Equation 8)

$$P = A_{surf} \cdot G_T \cdot \eta_{cell} \cdot \eta_{invert} \qquad \text{EQUATION 8}$$

where:

P [W] is an electrical power produced by photovoltaics,

A_{surf} [m^2] is an active PV cells net surface area,

G_T [W/m^2] is a total solar radiation incident on PV panel,

η_{cell} [-] is a PV panel conversion efficiency, and

η_{invert} [-] is a DC to AC conversion efficiency.

All parameters except for G_T are specified by the user. For simplicity, panel conversion efficiency and inverter conversion efficiency can be assumed to be constant. Average PV panel conversion efficiency is between 14% and 18% while the inverter operates for most of the time with more than 90% efficiency.

PV panels can be arranged in arrays which can be organized in rows to form a PV electricity generating plant. The size of the PV plant is often limited by available space, for example roof area or available plot of land. In some circumstances PV plant size can be constrained by electricity demand (e.g. the available space for PV plant can result in unnecessarily large electricity production).

The best orientation of PV panel in the northern hemisphere is usually due south. PV plants installed on the top of a flat roof should have the orientation between the South-East and the South-West. PV panel dimensions (length - PL and height - PH) are manufacturer specific while a PV array length (AL) is determined by a number of panels in the array (Figure 19). Optimal panel angle α is dependent on a few parameters, of which the latitude is one of the most important.

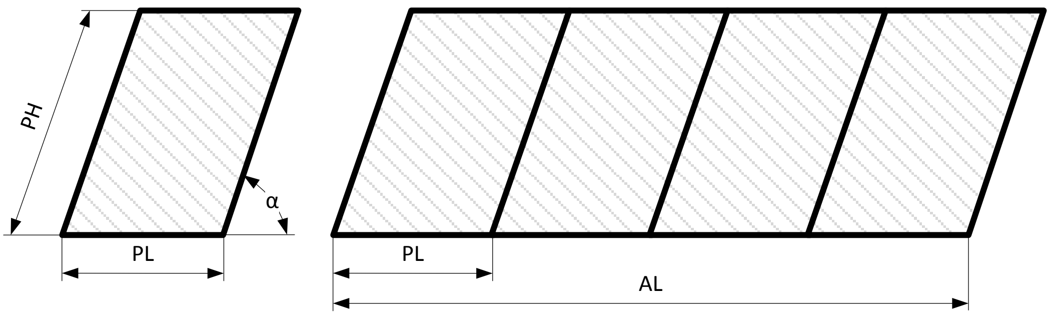

FIGURE 19 PV PANEL AND PV ARRAY DIMENSSIONS

The distance between PV arrays (D in Figure 20) is often driven by minimising the overshadowing of an array by the array in front. When the PV plant space is limited, the larger distance between arrays affects the total number of arrays which in turn limits the maximum PV plant output. PV panel angle also affects the distance between PV arrays.

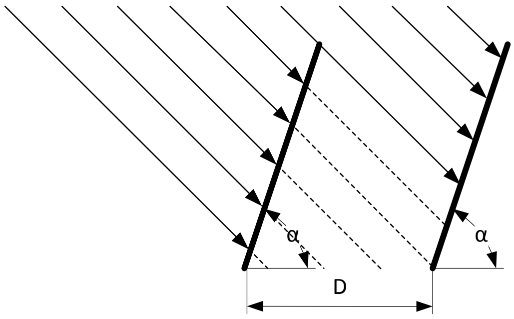

FIGURE 20 ROWS OF PV ARRAYS

Proper sizing of PV plant within the limited space can be difficult since there are multiple parameters which have to be defined. These parameters are:

- Panel length (PL),
- Panel height (PH),
- Tilt angle (α), and
- Distance between arrays (D)

The ultimate goal is to find optimal values for these parameters. However, to be able to find optimal values the optimisation objective has to be defined. The most common optimisation objective in sizing PV plants is the total annual electricity production. But the payback period is also an important parameter to take into consideration when specifying the size of PV plant. The payback period is calculated from investment costs (£ per KW of installed power) and assumed future cost of electricity. Having two objectives (the total annual electricity production and payback period), which conflict, means that there is no single optimal solution but a range of optimal solutions scattered on the Pareto front (red dots in Figure 21). The selection of an individual solution from a range of optimal solutions is the designer's responsibility.

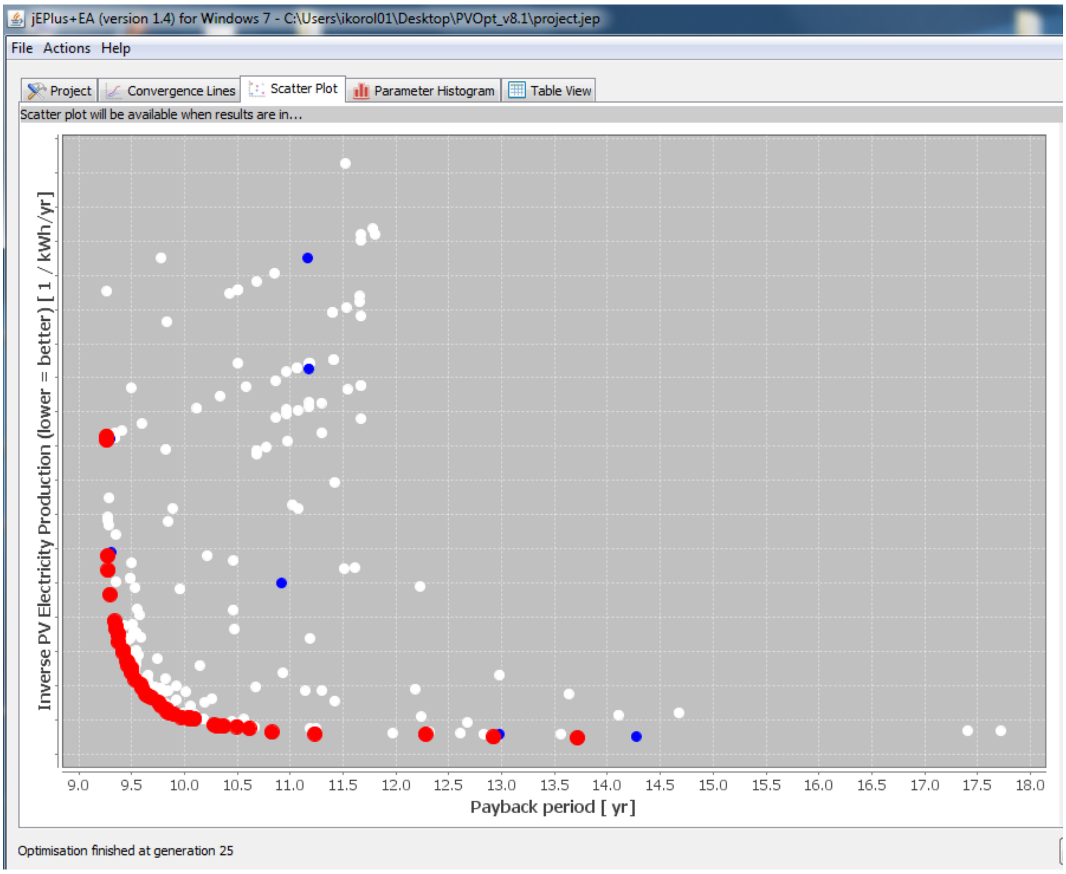

FIGURE 21 PARETO FRONT OF OPTIMAL SOLUTIONS

3.2 SOLAR THERMAL COLLECTORS

Solar thermal collectors are devices which convert solar energy into thermal energy by increasing the temperature of a heat transfer fluid which circulates through them. Thermal energy can be used for a range of applications such as domestic hot water, solar cooling, space heating, etc. The most common type of collector for commercial, residential, and low-temperature (<95°C) industrial applications is the flat-plate collector. Water is a commonly used as the heat transfer fluid in a flat-plate collector.

The main components of a flat-plate collector are an outside frame, insulation, a transparent cover (usually made from glass), an absorber plate and tubes for fluid flow (Figure 22). Tubes can be arranged in parallel or in a coil (rarely).

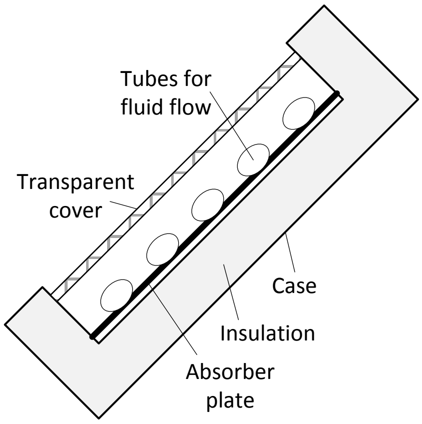

FIGURE 22 A FLAT-PLATE SOLAR THERMAL COLLECTOR

The calculation of flat-plate solar thermal collector performance has been thoroughly described by Duffie and Beckman [24]. In addition, ASHRAE Standards 93 [25] and 96 [26] describe the performance testing methodology of flat-plate solar collectors. The collector's thermal efficiency (η [-]) can be defined as a ratio of the collector's useful heat gain (q [W]) and the total incident solar radiation (I_{solar} [W/m^2]) on the collector's surface area (A [m^2]) as described by Equation 9.

$$\eta = \frac{q/A}{I_{solar}}$$ EQUATION 9

The collector's useful heat gain is affected by a complex relationship between transparent cover properties, absorber plate properties and environmental conditions. The complex interaction can be replaced by introducing empirically determined coefficients which leads to the representation of the collector's efficiency by Equation 10

$$\eta = c_0 + c_1 \cdot \frac{(T_{in} - T_{air})}{I_{solar}} + c_2 \cdot \frac{(T_{in} - T_{air})^2}{I_{solar}}$$ EQUATION 10

where:

T_{in} [°C] is the inlet temperature of the working fluid,

T_{air} [°C] is the temperature of the outdoor air, while

c_0, c_1, and c_2 are equation efficiency coefficients listed in the Directory of the Solar Rating and Certification Corporation (SRCC) [27]. SRCC applies ASHRAE Standards 93 and 96 in their rating procedures of solar collectors and publishes a database of ratings for commercially available collectors in North America. The database is a comprehensive source of specific information on the collectors certified under the various SRCC certification and rating programs.

The standardised test conditions determine the efficiency coefficients when the incident radiation is normal to the glazing surface; when the transmittance is highest. Position of the sun perpendicular to the surface of the collector rarely occurs. As with regular windows, the transmittance of the collector glazing varies with the incidence angle of radiation. For off-perpendicular angles, the transmittance of the glazing is modified by an incident angle modifier coefficient $K_{\tau\alpha}$ [-] which is a function of incident angle θ [°] (Equation 11). Both first-order and second-order incident angle modifier equation coefficients (b_0 [-] and b_1 [-]) are also listed in the Directory of SRCC Certified Solar Collector Ratings. Incident angle modifiers should be calculated separately for sun, sky, and ground radiation while the net incident angle modifier for all incident radiation is calculated by weighting each component by the corresponding modifier.

$$K_{\tau\alpha} = 1 + b_0 \cdot \left(\frac{1}{cos\theta} - 1\right) + b_1 \cdot \left(\frac{1}{cos\theta} - 1\right)^2 \qquad \text{EQUATION 11}$$

Incident solar radiation I_{solar} includes beam and diffuse radiation, as well as radiation reflected from the ground and adjacent surfaces. It is also important to take into account the shading of a collector by other surfaces, such as nearby buildings or trees. The outlet temperature of the working fluid (T_{out} [°C]) can be calculated by Equation 12

$$T_{out} = T_{in} + \frac{q}{\rho \cdot \dot{V} \cdot c_p \cdot A} \qquad \text{EQUATION 12}$$

where:

ρ [kg/m^3] is a working fluid density,

$\dot{V}$ [m^3/s] is a volume flow rate,

c_p [J/kg-K] is the working fluid specific heat.

Most commercial and industrial systems require a large number of collectors which are often grouped in arrays. A series of arrays forming a solar collector field can be connected in parallel flow or series-parallel flow. Parallel flow is the most commonly used since it is more easily balanced and has a lower pressure drop. The size of a solar collector field is often limited by available space and it is usually driven by heating demand. In addition, the outlet temperature of the working fluid affects the size. A solar thermal system often uses some form of heat storage which increases the sizing complexity. On top of this, collector thermal characteristics, geometry, distance between arrays, orientation, tilt angle, working fluid, and outdoor environmental conditions all affect the system performance. These are all parameters for which optimal values can be determined by using multi-objective optimisation, similar to the calculation explained in the photovoltaic section.

3.3 Solar Concentrators

Parabolic trough collectors (Figure 23) concentrate the direct solar radiation onto an absorber tube, by means of a reflective surface (mirror), in order to produce medium temperatures in the heat transfer fluid that flows along it, which can be water or thermal oil, depending on the final required temperature.

The demineralized water or a mixture of an antifreeze (e.g. ethylene glycol, propylene glycol, etc.) can be used in case of lower temperatures (< 120°C). For higher temperatures either a synthetic thermal oil or demineralized water (pressurised or direct steam generation) is used. For the pressurised water and for the direct steam generation special measures for frost protection are required.

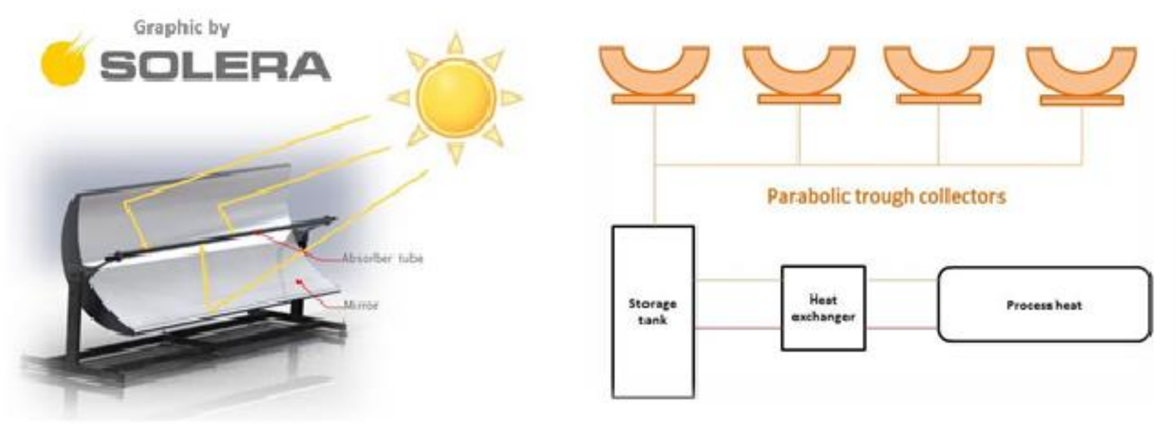

FIGURE 23 FUNCTIONAL PRINCIPLE OF PARABOLIC TROUGH COLLECTORS (SOURCE: SOLERA)

Concentrating collectors can only use the direct solar irradiation, and due to that, have a tracking system in order to modify the mirror position and concentrate the maximum direct solar radiation throughout the day. Parabolic trough collectors are normally north-south oriented and track from east to west. The reason is that with this orientation, the total yield obtained among the year is normally higher. Nevertheless east-west oriented collectors are also a valid solution, and with this orientation the yield is normally more homogeneous among the year. The total efficiency of the collector depends on multiple factors, as the ones involved in the optical and thermal efficiency.

The technology modelling for the solar concentrator (parabolic trough collector) is based on a macro scale as a “black-box” approach. Therefore, the specific inputs, parameters and collector efficiency and solar energy output are shown in Figure 24.

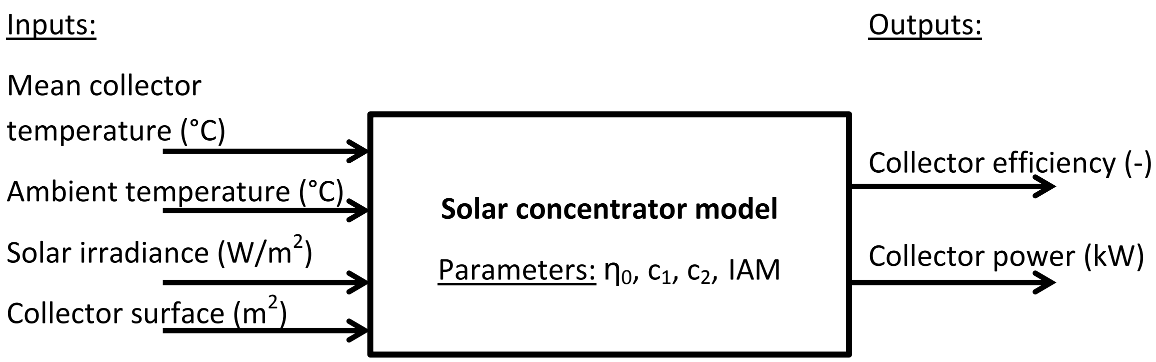

FIGURE 24 MODEL OF SOLAR CONCENTRATOR (SOURCE: JER)

In the following paragraphs the different equations for the modelling of the solar concentrator technology are described in detail. The collector efficiency in a steady state (i.e. with no change of operating conditions) is defined as (Equation 13):

$$\eta = \frac{instantaneous\ collector\ power}{incident\ radiation\ on\ collectors\ area} = \frac{\dot{Q}_{coll}}{A \cdot G}$$ EQUATION 13

where:

A [m^2] is the aperture or absorber area of collector, depending on chosen reference,

G [W/m^2] is the incident global solar irradiance on the collector aperture,

$\dot{Q}_{coll}$ [W] is the usable thermal power of the collector.

The collector efficiency can also be calculated for steady-state operation using temperature instead of collector power and aperture area (Equation 14):

$$\eta = \eta_0 - k(\Theta) - c_1 \cdot \frac{\Delta T}{G} - c_2 \cdot \frac{\Delta T^2}{G}$$ EQUATION 14

where:

η_0 [-] is the optical collector efficiency,

c_1 [W/m^2-K] is the linear loss coefficient,

c_2 [W/m^2-K^2] is the quadratic loss coefficient,

$k(\Theta)$ [-] is the incident angle modifier (IAM),

ΔT [K] is the temperature difference between mean collector temperature and the ambient temperature (Equation 15).

$$\Delta T = T_m - T_{Amb} = \frac{T_{coll,in} + T_{coll,out}}{2} - T_{Amb}$$ EQUATION 15

where:

$T_{coll,in}$ [K] is the inlet temperature of collector heat transfer fluid,

$T_{coll,out}$ [K] is the outlet temperature of collector heat transfer fluid.

The collector coefficients η_0, c_1, c_2 and the incident angle modifier $k(\Theta)$ are usually given by manufacturers or can be found in the test reports of collector test centres.

The incident angle modifier $k(\Theta)$ represents the influence of the radiation incident angle on the optical performance of the solar collector. It is an important parameter that accounts for the effect of non-orthogonal light falling onto the collector and the resulting losses or gains in collector power. It is expressed as a differential change in collector efficiency compared to the efficiency value for light falling orthogonally onto the collector. For stationary or single-axis tracking collectors the IAM is per definition equal to 1 at normal incident radiation (radiation falling orthogonally onto the collector surface).

For single-axis tracking collectors two IAM values have to be provided, one to account for the longitudinal (parallel to the tube length) and one for the transversal (crosswise to the tube length) direction. A single IAM value for single-axis tracking collectors can then be calculated using the following equation:

$$k(\Theta) = k_{LONG}(\Theta) \cdot k_{TRANS}(\Theta)$$ EQUATION 16

where:

$k(\Theta)$ [-] is the total incident angle modifier (IAM),

$k_{LONG}(\Theta)$ [-] is the incident angle modifier for the longitudinal (parallel to the tube length) axis of the collector,

$k_{TRANS}(\Theta)$ [-] is the incident angle modifier for the transversal (crosswise to the tube length) axis of the collector.

The presented collector efficiency equations are for steady-state operation of the collector. It does not account for transient effects, such as the dynamic heating and cooling of the collector during operation due to its heat capacity. Also, no difference is being made between the incidence angle modifier for direct and diffuse radiation.

3.4 Hot Water Storage

A hot water storage device may be used to store thermal energy in order to decouple supply and demand to some extent. Typical hot water storage applications are for domestic hot water (DHW), low-temperature space heating, and energy storage for solar thermal collectors or waste heat recovery. Hot water storage, simplified shown in Figure 25, is usually part of a bigger system. The supply side typically draws hot water from the water heater and returns cooler water while the demand side draws hot water from the hot water storage and returns cooler water. The supply side can be attached to solar thermal collectors or a waste heat recovery system and may be augmented by a backup heating system such as a separate boiler. The demand side can be attached directly to the heat sink within an industrial facility or to other components of the system such as an absorption chiller.

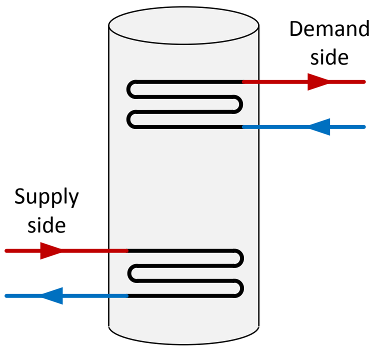

FIGURE 25 HOT WATER STORAGE

Simplified models of hot water storage assume that all water in the tank is at the same temperature (i.e. a well-mixed water tank). More complex models take into consideration the stratification effect. The energy balance of the well-mixed water tank is presented in Equation 17

$$\rho \cdot V \cdot c_p \cdot \frac{dT}{dt} = q_{net} \qquad \text{EQUATION 17}$$

where:

ρ [kg/m^3] is a water density,

V [m^3] is a tank volume,

c_p [J/kg-K] is a water specific heat,

T [°C] is a water temperature,

t [s] is a time, and

q_{net} [W] is a net heat transfer rate to a tank water.

The net heat transfer to a water tank is a sum of all gains and losses which occur in the tank (Equation 18)

$$q_{net} = q_{heater} + q_{demand} + q_{supply} + q_{loss}$$ **EQUATION 18**

where:

q_{heater} [W] is a heat added by the heating element or burner. This is common for hot water storage systems which have a backup heater (electric or gas),

q_{demand} [W] is a heat transfer to a demand side fluid stream,

q_{supply} [W] is a heat transfer from a supply side fluid stream,

q_{loss} [W] is a heat loss (or sometime gain) to an ambient environment.

Heat loss to the ambient environment can be calculated by using Equation 19 while a heat transfer to a demand side fluid stream and heat transfer from a supply side fluid stream are presented in Equation 20

$$q_{loss} = UA \cdot (T_{amb} - T)$$ **EQUATION 19**

$$q_{demand/supply} = \varepsilon_{demand/supply} \cdot \dot{m}_{demand/supply} \cdot c_p \cdot \left(T_{demand/supply} - T\right)$$ **EQUATION 20**

where:

UA [W/K] is a heat loss coefficient to ambient environment,

T_{amb} [°C] is an ambient temperature,

$\varepsilon_{demand/supply}$ [-] is a demand/supply heat exchanger effectiveness,

$\dot{m}_{demand/supply}$ [kg/s] is a demand/supply side fluid mass flow rate,

c_p [J/kg-K] is a demand/supply side fluid specific heat, and

$T_{demand/supply}$ [°C] is an inlet demand/supply side fluid temperature.

Solving a differential Equation 17 the temperature of the tank water at time t can be calculated (for known initial temperature T_i at time $t = 0$) or time required to reach desired tank water temperature.

The hot water storage volume and/or capacity can be determined by several methods. When the demand side requirements are known, the tank size can be based on how long it can meet the demand and how quickly it can recover. In installations with solar collectors the tank volume may be based on the total collector area by using a design rule from one of the various design guides.

3.5 Lithium-Ion Batteries

The battery model is made for a NMC Li-ion battery (KOKAM SLPB100216216H, 40Ah) but the idea is that it can be used also for other chemistries and cells by simply adapting the Equivalent Circuit Model (ECM) model parameters.

For this purpose a 2nd order Randles model, composed of 2 RC branches or time constants is selected, one representing the high frequency and the other one the low frequency (search the time constants). The second order model is chosen because of the good trade-off between complexity and accuracy.

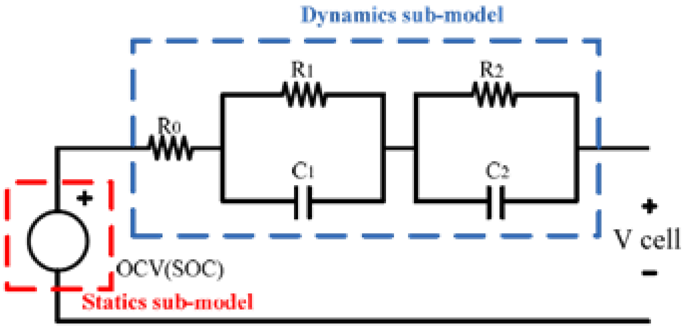

FIGURE 26 2ND ORDER RANDLES MODEL

For modelling the battery we need charge and discharge curves from the datasheet of the battery, the experimental measurement of the internal resistance in function of time, temperature and SOC, and the experimental OCV vs. SOC measurements for charge and discharge procedures.

The extraction of the RC-parameters is done using a toolbox, the obtained voltage correlation is quite well. The name Profile1 will be further always used as the name for the pulse profile.

FUDS (Federal Urban Driving Schedule) is used for validation of the electric model to see if the parameterization is valid for the whole range of SOC.

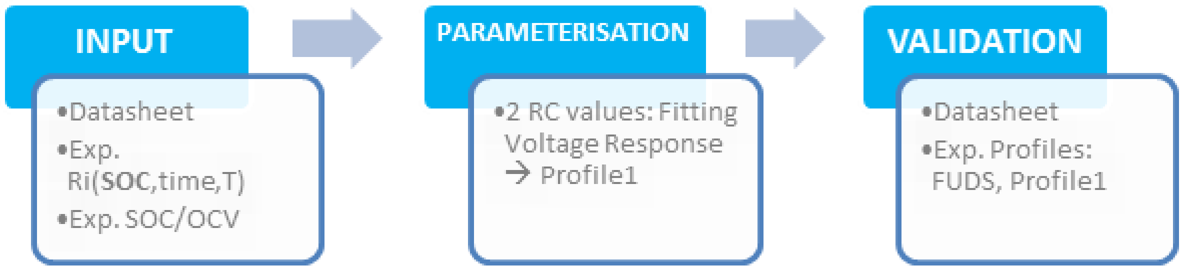

FIGURE 27 ECM INPUTS, PARAMETERISATION AND VALIDATION PROCEDURE

The battery model was developed in Matlab Simulink, and can handle a power or current input. Initially the battery model can handle only a current input but due to the easy implementation possibilities in Simulink, the current can also be calculated from the power input by using a feedback loop and an Initial Condition block (IC-block).

The model requires the initialisation of parameters like the battery initial state of charge (SOC_0), nominal capacity, RC-parameters and the initial voltage when a power input is used. On the other hand, there are several stop criteria like SOC going out of the limits of 0% and 100%, voltage at battery terminals (Vbat) out of the limits of cut-off voltage of 2.7V and 4.15V or, in a satisfactory case, end of input profile.

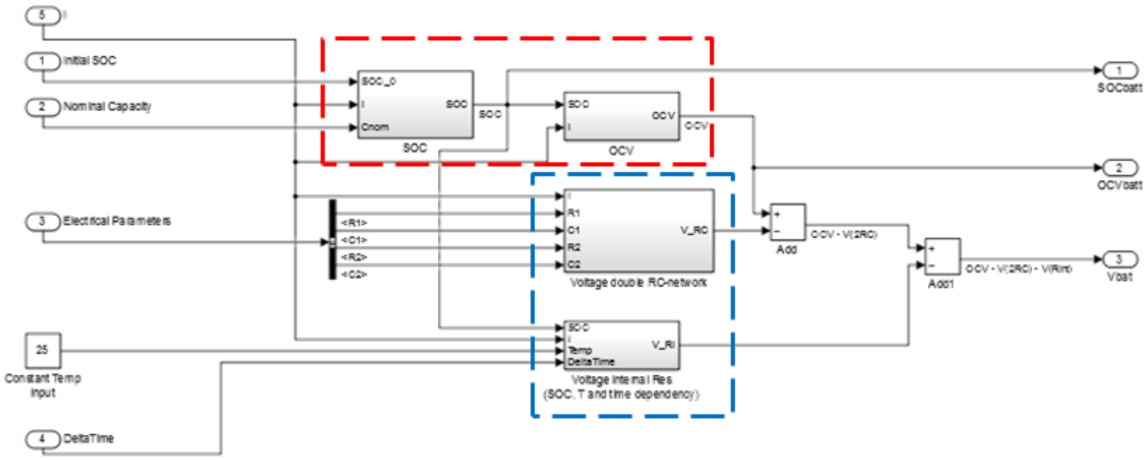

FIGURE 28 BATTERY ELECTRICAL MODEL PLATFORM IN SIMULINK

The FUDS profile in total is a composition of multiple FUDS profiles (each of +- 22min) after each other. In total we have almost 5 FUDS profiles after each other. The Simulink files for the FUDS, Profile1 and WLTC are adapted such that only the discharging SOC vs. OCV relation is used. In this way the graphs are made with only the discharge SOC vs. OCV relation.

The difference in the beginning of the voltage response (Figure 29) is due to the adapted input profile (omitting charge part) because the CV charge cannot be simulated with this model. There is also a relatively large difference at low SOC values. This is due to the remarks made at the SOC vs. OCV relation. Less accuracy is obtained at low SOC values and this causes the premature drop in simulated voltage.

For the FUDS profile as well as Profile 1 we can notice that the own made model is better as the Matlab model by comparison with the experimental data. See also that, again, because the FUDS profile go into low regions of SOC, again the same difference is noticed in the end.

Also the WLTC profile is introduced here (7after each other) to show the effect of the different voltage on the SOC calculation. Normally the calculation of the SOC is the same for both IK4-Ikerlan model and the one of Matlab.

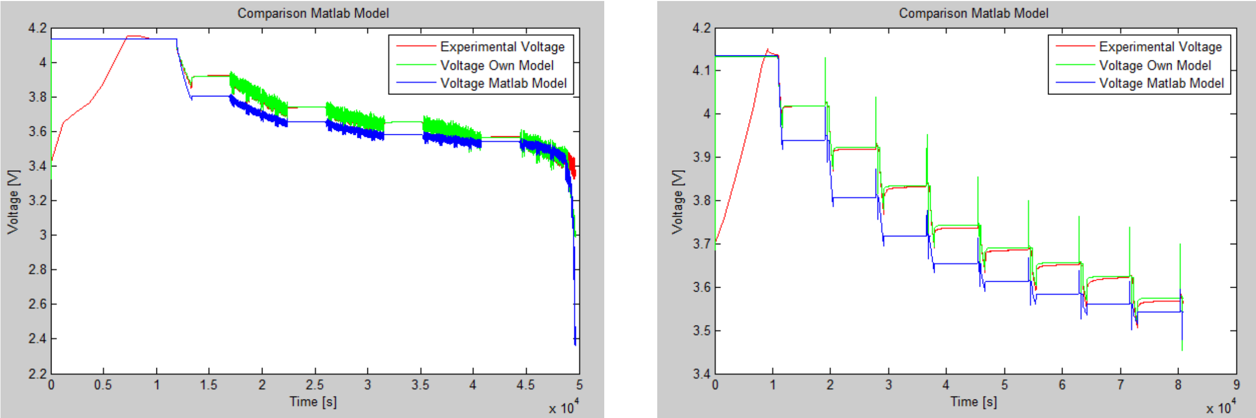

FIGURE 29 BATTERY ELECTRICAL MODEL VALIDATION, (A) 4 FUDS PROFILES, (B) PULSE TEST (WLTC)

3.6 Solar Cooling System

A solar cooling system is a system comprising multiple devices assembled together, with the main aim of using solar energy to meet a cooling demand. A schematic representation of a solar cooling system is presented in Figure 30, which shows that the core element of a solar cooling system is an absorption chiller. An absorption chiller is a cooling machine which uses a heat source to provide the energy needed to drive a cooling system, instead of the electricity that is used by conventional compression machines; hence the electricity demand of an absorption chiller is significantly lower compared to a conventional chiller of the same-capacity. On the other hand, the thermal performance of an absorption chiller is such that this technology is inferior to conventional systems except in cases when there is a source of low cost heat available, such as solar heat, waste heat, or as a part of tri-generation system. In solar cooling applications, the heat required for operation of an absorption chiller is generated in a solar collector plant. Since there is usually a mismatch between cooling demand and available solar heat, hot water storage is usually installed between a solar collector plant and an absorption chiller. An absorption chiller rejects heat to the environment via a cooling tower or a dry cooler. As mentioned in section 2, meeting cooling demand is of great importance in industrial facilities, which means that a backup system has to be installed to support the operation of a solar cooling system. Two types of a backup system can be installed: an additional conventional chiller or a backup heater. The conventional chiller can be placed in the cooling demand loop to respond to cooling demand that the absorption chiller cannot meet due to lack of available heat from a solar collector plant. Another approach is to include a backup heater which will provide additional heat whenever there is a shortage of heat from the solar collector plant. The additional backup heater can be either electric or a gas-fired boiler. The decision on which type of backup system is more applicable has to be made after careful analysis of cooling demand profile and heat generation potential of solar plant.

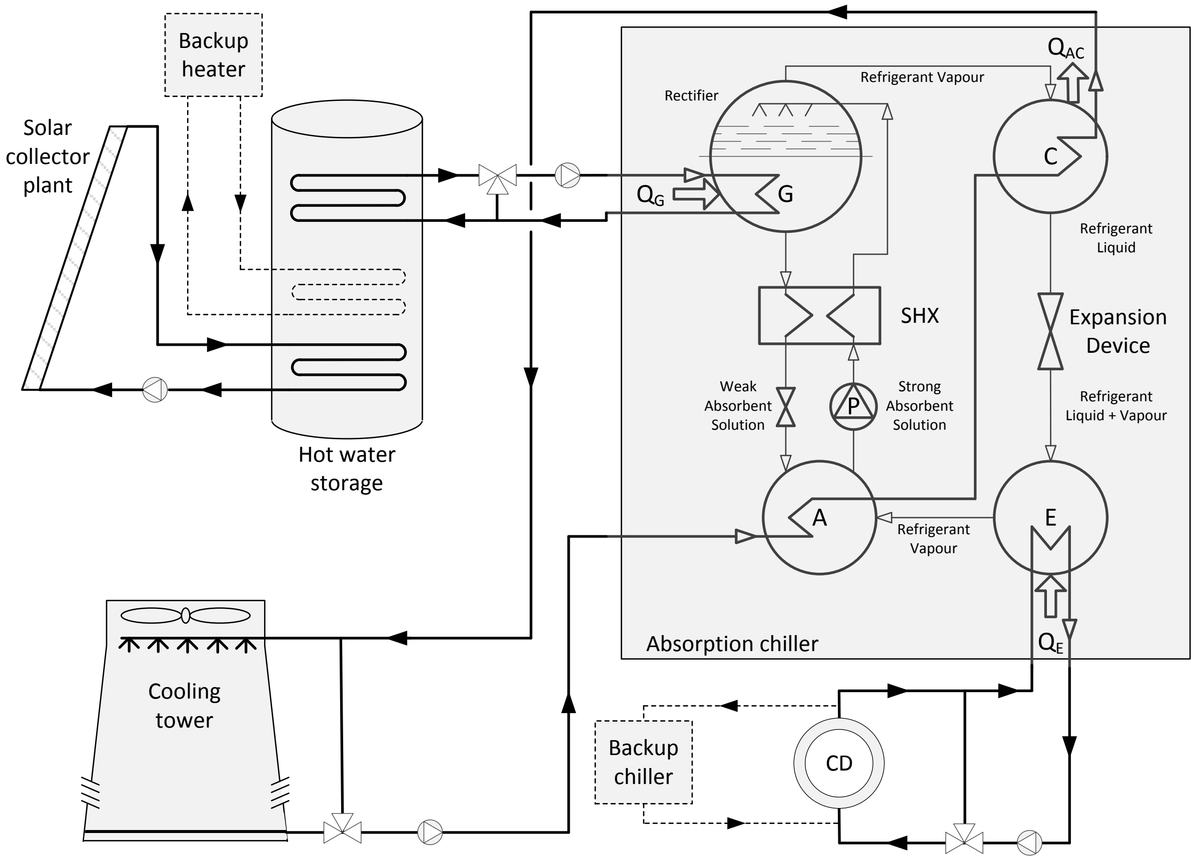

FIGURE 30 SOLAR COOLING SYSTEM

The overall performance of a solar cooling system is affected by the performance of individual devices that the system is made from, which complicates the modelling of such a system. The theoretical background of solar thermal collectors and hot water storage has been covered in previous sections.

3.6.1 ABSORPTION CHILLER

The operation of an absorption chiller is based on the sorption process in which a liquid or solid sorbent absorbs refrigerant molecules and the resulting mixture starts to change physically and chemically during the process that follows. The working principle is based on the different boiling points of the refrigerant and the absorbent. The single-effect NH_3-H_2O absorption chiller (Figure 31), consists of a generator with rectifier (G), a condenser (C), an evaporator (E), an absorber (A), solution heat exchanger (SHX), solution pump (P) and two throttling valves. External heat input to the generator causes the refrigerant to boil out of solution. Once in the vapour state it is compressed at higher pressure while the concentrated absorbent remains liquid. The rectifier is an additional device which provides the purity of the refrigerant vapour before entering to the condenser. Inside the condenser, refrigerant vapour condenses by transferring the heat to the external heat carrier (usually water) circuit. The external heat carrier circuit is typically connected to a cooling tower or a dry cooler enabling the heat rejection to the surrounding. The condensed liquid refrigerant flows through an expansion device into the evaporator. Inside the evaporator, the refrigerant receives the heat from another external heat carrier circuit and evaporates, producing the cooling effect on the circulating water. The low pressure refrigerant vapour then proceeds to the absorber where it is absorbed by the weak absorbent solution. The absorbed refrigerant vapour condenses to a liquid, releasing the heat received in the evaporator to the external heat carrier circuit. This circuit is usually designed to be common for absorber and condenser (cooling water circuit). The strong absorbent solution is then pumped through the solution heat exchanger to the generator where heat is used to separate the refrigerant again.

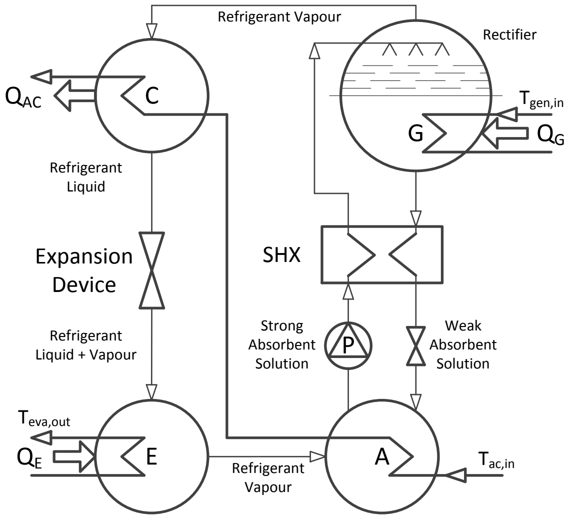

FIGURE 31 ABSORPTION CHILLER

The performance of an absorption chiller is affected by its operating conditions, in particular the cooling load and temperatures of liquids in the three circuits (generator, evaporator and absorber-condenser). Figure 32 shows a chiller's performance map for a constant evaporator leaving temperature. The black line represents the optimal chiller operation. If the inlet generator temperature and inlet absorber-condenser temperature are kept on the black line for various actual loads, the chiller will operate at the maximum coefficient of performance (COP) for those conditions. However, it also can be seen that the COP drops significantly at low loads.

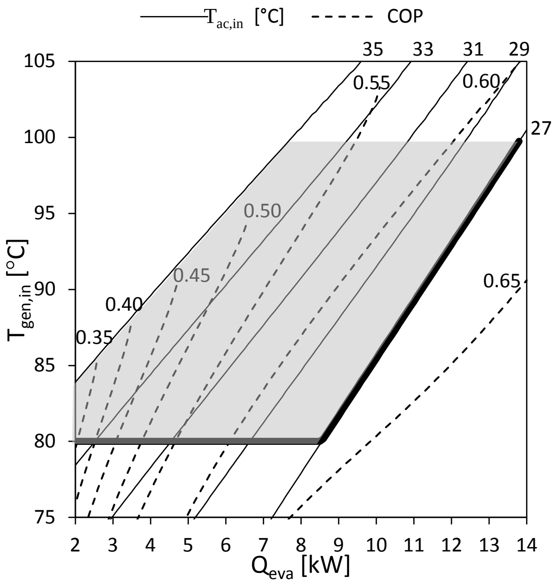

FIGURE 32 ABSORPTION CHILLER PERFORMANCE (FOR T_{EVA}=7°C)

According to the improved BLAST model [28], the maximum absorption chiller capacity ($Q_{eva,max}$ [W]) can be calculated as presented in Equation 21

$$Q_{eva,max} = Q_{eva,nom} \cdot CAPFT_{eva,out} \cdot CAPFT_{gen,in} \cdot CAPFT_{ac,in} \quad \text{EQUATION 21}$$

where:

$Q_{eva,nom}$ [W] is the nominal chiller capacity obtained from a manufacturer based on standardised rating procedures,

$CAPFT_{eva,out/gen,in/ac,in}$ [-] are capacity correction factors as a function of evaporator outlet temperature ($T_{eva,out}$ [°C]), generator inlet temperature ($T_{gen,in}$ [°C]) and absorber-condenser inlet temperature ($T_{ac,in}$ [°C]). These factors can be calculated by cubic equations (Equation 22) for which parameters can be obtained from manufacturers.

$$CAPFT_{eva,out/gen,in/ac,in} = a0_{eva,out/gen,in/ac,in} + a1_{eva,out/gen,in/ac,in} \cdot \left(T_{eva,out/gen,in/ac,in}\right) + a2_{eva,out/gen,in/ac,in} \cdot \left(T_{eva,out/gen,in/ac,in}\right)^2 + a3_{eva,out/gen,in/ac,in} \cdot \left(T_{eva,out/gen,in/ac,in}\right)^3 \quad \text{EQUATION 22}$$

The part-load ratio (PLR) of the absorption chiller's evaporator is a ratio of the actual cooling load (Q_{eva} [W]) and the maximum cooling capacity ($Q_{eva,max}$) as presented in Equation 23.

$$PLR = Q_{eva}/Q_{eva,max} \quad \text{EQUATION 23}$$

The heat input to the chiller's generator is also a function of several parameters (Equation 24) in particular the chiller's maximum cooling capacity ($Q_{eva,max}$), the ratio of generator heat input to chiller operating capacity ($GenHIR$ [-]) and a couple of correction coefficients ($GenT_{gen,in}$ [-] and $GenT_{eva,out}$ [-]) which modify the heat input requirement based on the generator inlet water temperature and the evaporator outlet water temperature.

$$Q_{gen} = GenHIR \cdot Q_{eva,max} \cdot GenT_{gen,in} \cdot GenT_{eva,out}$$ EQUATION 24

The generator heat input ratio is a cubic function of chiller's part load ratio (Equation 25) which parameters should be obtained from manufacturer.

$$GenHIR = b0 + b1 \cdot PLR + b2 \cdot PLR^2 + b3 \cdot PLR^3$$ EQUATION 25

Correction coefficients $GenT_{gen,in}$ and $GenT_{eva,out}$ are also presented by cubic curves (Equation 26)

$$GenT_{gen,in/eva,out} = c0 + c1 \cdot (T_{gen,in/eva,out}) + c2 \cdot (T_{gen,in/eva,out})^2 + c3 \cdot (T_{gen,in/eva,out})^3$$ EQUATION 26

Absorption thermal coefficient of performance can be calculated from actual cooling load and generator's heat requirements as presented in Equation 27.

$$COP = \frac{Q_{eva}}{Q_{gen}}$$ EQUATION 27

The heat rejected to the environment via a cooling tower or a dry cooler is the sum of cooling load, generator heat and auxiliary heat gain from the chiller pump (Equation 28)

$$Q_{ac} = Q_{eva} + Q_{gen} + Q_{pump}$$ EQUATION 28

The heat transfer equation can be applied to determine the missing parameters (mass flow rate or temperature drop/rise) of the three chiller circuits by considering whether the flow is variable or constant.

3.6.2 COOLING TOWER

A cooling tower is a device which rejects condenser heat to the atmosphere by evaporative cooling. There are two types of cooling tower; open circuit and closed circuit. In a closed circuit cooling tower, condenser water is circulated in a closed loop and a separate water circuit is used to pump water through a cooling tower, cooling the condenser water using a heat exchanger. This minimises water treatment costs but it also reduces energy efficiency due to the temperature difference across the heat exchanger. In open circuit cooling towers, water from a condenser is pumped to a cooling tower where it is cooled by evaporation of some of the condenser water. This requires all the water passing through a condenser to be treated.

Air flow in cooling towers is usually forced by fans, which can be single-speed, two-speed or variable speed. The capacity of single-speed and two-speed cooling towers is controlled either by fan cycling between on and off or by water bypass. The capacity of variable speed cooling towers is controlled by modulating the air flow between maximum (full load) and minimum flow (usually not less than 30% of maximum flow). When operated at loads below minimum, the variable-speed cooling tower is cycled between on and off. A cooling tower rejects heat by natural convection when the fan is off.

Cooling towers are usually controlled by maintaining the leaving water temperature at a desired setpoint. There are two approaches to modelling the performance of cooling towers. The first one is based on effectiveness-NTU relationships (where NTU means number of transfer units) for counterflow heat exchangers while the second one is based on fitting empirical curves for the manufacturer's performance data or field measurements. The best known model based on the effectiveness-NTU approach is described in the ASHRAE Primary Toolkit [29] and is based on Merkel's theory [30].

Empirical models (based on manufacturer's performance data or field measurements) use tower performance at design conditions and empirical curves to determine tower heat rejection and fan power at off-design performance. Tower performance at design conditions is defined by an inlet air wet-bulb temperature, tower range, and tower approach temperature. The corresponding water flow rate, air flow rate, and fan power must also be specified. Empirical curves are used to determine the approach temperature and fan power at part load conditions.

In the case where the field measurements cannot be obtained, a well-validated empirical model, based on either the CoolTools [31] correlation or YorkCalc [32] correlation, can be used. These correlations determine the tower approach temperature using a polynomial curve fit with a large number of model coefficients and either four or three independent variables respectively. The CoolTools correlation has 35 model coefficients with four independent variables. The approach temperature [°C], which is a difference between outlet water temperature ($T_{w,out}$ [°C]) and inlet air wet-bulb temperature ($T_{air\_wb,in}$ [°C]), is a function of air flow ratio FRair [-] (actual air flow rate divided by design air flow rate), water flow rate ratio FRwater [-] (actual water flow rate divided by design water flow rate), inlet air wet-bulb temperature ($T_{air\_wb,in}$ [°C]) and range temperature T_r [°C] (the difference between inlet water temperature ($T_{w,in}$ [°C]) and outlet water temperature ($T_{w,out}$ [°C])), as shown in Equation 29.

$$Approach = f(FRair, FRwater, T_{air\_wb,in}, T_r) \quad \text{EQUATION 29}$$

Similarly, the YorkCalc correlation has 27 model coefficients with three independent variables: range temperature T_r [°C], inlet air wet-bulb temperature ($T_{air\_wb,in}$ [°C]) and liquid-to-gas ratio LGratio [-] which is ratio of water flow rate ratio (FRwater) and air flow rate ratio (FRair), Equation 30.

$$Approach = f(LGratio, T_{air\_wb,in}, T_r) \quad \text{EQUATION 30}$$

The fan electric power is calculated based on the air flow rate ratio required to meet the tower's capacity. If a fan power cubic curve is not available, it can be assumed that tower fan power is directly proportional to the cube of the air flow rate ratio.

3.7 Combined Heating, Power And Cooling (CHPC)

A combined heating, power and cooling system (also known as a tri-generation system) is a system which generates electricity while heat recovered from electricity generation is used either to directly provide heating energy or to provide cooling energy by using thermally driven chillers (Figure 33). The electricity generator can be driven either by an internal combustion engine, a gas turbine/micro-turbine (example in Figure 33), a steam turbine, a Stirling engine or by fuel cells.

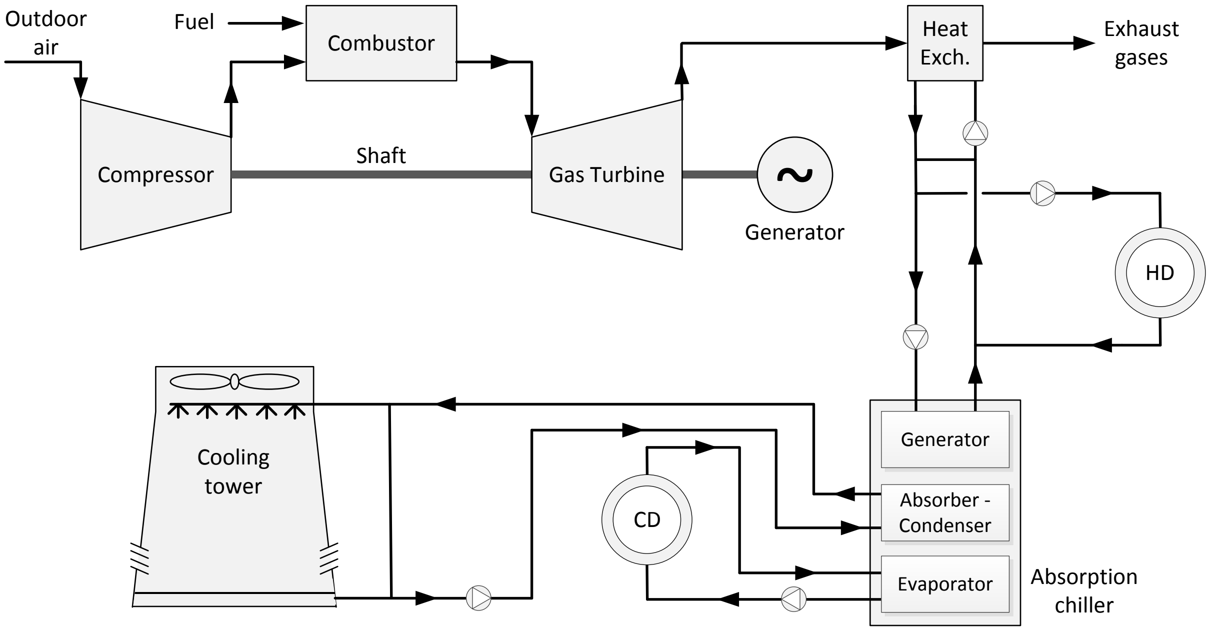

FIGURE 33 COMBINED HEATING, POWER AND COOLING (CHPC) SYSTEM

A gas turbine generator comprises three main elements: the compressor, the combustor and the turbine. Atmospheric air is drawn into a rotational machine where its pressure is raised by a dynamic air compressor attached to a shaft driven by a gas turbine. Compressed air is mixed with fuel and ignited in a combustor under constant pressure conditions. The resulting hot gas expands through the turbine to perform work transferred to the shaft. Some of the power produced in a turbine is used to drive the air compressor while the remainder is available to drive a generator, hence to produce electricity.

The fuel energy input (FEI [J/s]) of the gas turbine generator can be calculated as a function of an electric energy output (EEO [W]), a part load ratio (PLR [-]) and an inlet air temperature, as presented in Equation 31.

$$FEI = EEO \cdot (a1 + a2 \cdot PLR + a3 \cdot PLR^2) \cdot (b1 + b2 \cdot \Delta T + b3 \cdot \Delta T^2)$$ EQUATION 31

Part load ratio is a ratio between EEO and nominal generating capacity (NGC [W]). ΔT is the temperature difference between actual inlet air temperature (T_{air} [°C]) and a design inlet air temperature (T_{design} [°C]) provided by manufacturer. The equation coefficients also have to be derived from manufacturers' data. In addition to fuel energy input, it is useful to know the exhaust gas temperature, particularly when rejected heat can be recovered and reused. The exhaust gas temperature ($T_{exhaust}$ [°C]) is also calculated as a function of LR , ΔT and equation coefficients provided by turbine manufacturer (Equation 32).

$$T_{exhaust} = (c1 + c2 \cdot PLR + c3 \cdot PLR^2) \cdot (d1 + d2 \cdot \Delta T + d3 \cdot \Delta T^2)$$ EQUATION 32

The exhaust gas mass flow rate ($\dot{m}_{exhaust}$ [kg/s]) is used to determine the heat recovery potential. Mass flow rate is calculated as a product of nominal generating capacity (NGC) and a quadratic function of ΔT (Equation 33).

$$\dot{m}_{exhaust} = NGC \cdot (f1 + f2 \cdot \Delta T + f3 \cdot \Delta T^2) \quad \text{EQUATION 33}$$

More advanced models take into consideration the elevation of a location where a gas combustion turbine is installed due to the impact of elevation on the atmospheric air pressure.

The sizing of a tri-generation system is usually driven by electricity generation requirements. Heat recovered from the exhaust gases is used for covering (partially) both heating and cooling demands. The system operates well in applications with a strong distinction between seasonal cooling/heating requirements. In cases where both heating and cooling have to be provided simultaneously, cooling requirements are usually fulfilled first. In a tri-generation system, cooling energy is generated in an absorption chiller. The absorption chiller has to be linked to heat rejection equipment such as a cooling tower or dry cooler. The sizing and modelling of absorption chillers and cooling towers have been described in previous section.

3.8 Organic Rankine Cycle (ORC)

The working principle of the organic Rankine cycle (ORC) is same as the steam Rankine cycle, with the main difference being the working fluid used in each cycle. The working fluid in a steam Rankine cycle is water, while there are literally hundreds of different working fluids can be used in an ORC [33] with many new ones being designed and discovered frequently. One of the main issues in designing an ORC is selection of the optimal working fluid, which is mainly related to temperatures of the heat source and heat sink. For any temperature level there are a number of suitable fluids, which does not make a selection of working fluid straight-forward. The working fluid selection process is usually a trade-off between thermo-physical properties of a fluid and safety, environmental and economic aspects [34].

A generator using the ORC has four main components (as with a generator based on the steam Rankine cycle): the evaporator, condenser, expander and pump. The pump pressurises a working fluid which is distributed to an evaporator (heat source) where it change phase to vapour which is expanded in a turbine (connected to the generator) and finally condensed in the condenser (heat sink). There are three types of organic cycles depending on where these four processes occur:

1. Subcritical ORC. In this cycle the four processes occur at pressures lower than the critical pressure for the working fluid.
2. Trans-critical ORC. Heat addition to the working fluid happens at a pressure higher than critical, while heat rejection happens at a pressure lower than critical.
3. Supercritical ORC. All four processes occur at pressures higher than the critical pressure.

The four processes of the subcritical ORC are shown in the temperature-entropy diagram in Figure 34. The process of adding heat to a working fluid occurs between points 1 and 2. Expansion in the turbine is represented by the line connecting points 2 and 3. This is not an isentropic process (s≠constant) due to turbine losses. The line connecting points 3 and 4 represents the heat rejection process in a condenser.

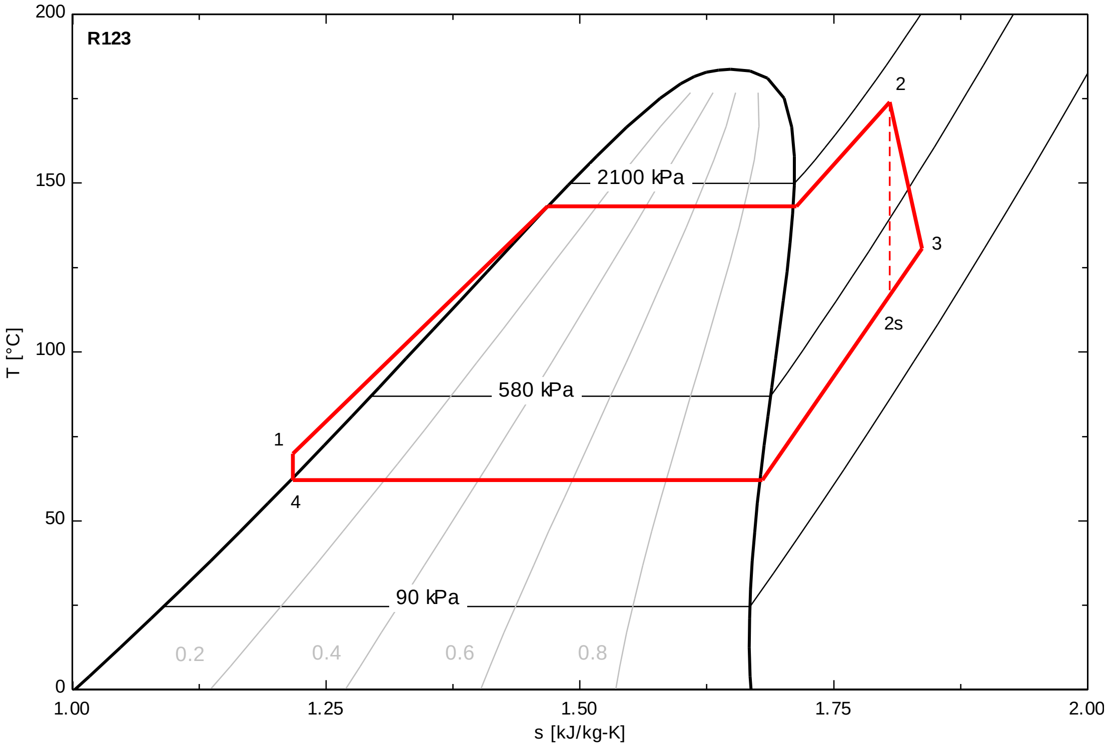

FIGURE 34 ORGANIC RANKINE CYCLE

The main benefit of the ORC, compared the Rankine cycle, is that energy can be extracted (hence electricity can be generated) from heat sources at much lower temperatures. The heat source temperature for an ORC can vary from 50°C to over 250°C. This makes the ORC a rational choice for energy extraction from industrial waste heat, gas turbine exhaust heat, solar thermal energy, etc. The ORC evaporator can be coupled to a heat source either directly (energy is directly exchanged between the source and ORC working fluid) or indirectly (energy is exchanged between source and ORC working fluid by using additional heat exchanger in a separate loop). In applications where a liquid energy carrier can be used between the heat source and the ORC, the evaporator is usually directly connected to the source, while in cases where heat is extracted from gases, an ORC evaporator is commonly connected indirectly to the source via a separate loop typically filled with thermal oil or pressurised water.

An ORC system can be analysed by simplified calculation based on the specific enthalpies (h [J/kg]) of characteristic ORC process steps (presented in Figure 34). It is important to know the temperature of a heat source and a heat sink to choose an ORC working fluid and ORC evaporator and condenser pressure levels. The maximum ORC temperature (stage 2 in Figure 34) should be lower by at least 20°C than the heat source temperature in order to improve heat transfer. The available heat from a heat source Q [W] can be used to calculate the flow rate $\dot{m}$ [kg/s] of the ORC working fluid (Equation 34).

$$Q = \dot{m} \cdot (h_2 - h_1)$$ **EQUATION 34**

The work generated in the turbine (W_T [W]) can be calculated by multiplying the turbine isentropic efficiency η_T (usually around 0.9) by mass flow and change in specific enthalpy, assuming ideal isentropic expansion between evaporation and condensation pressures (Equation 35).

$$W_T = \dot{m} \cdot (h_2 - h_{2S}) \cdot \eta_T$$ **EQUATION 35**

Finally, the electricity generated (E_G [W]) can be calculated by multiplying work generated in a turbine with generator efficiency η_G (Equation 36).

$$E_G = W_T \cdot \eta_G$$ **EQUATION 36**

Information on the thermophysical properties of various ORC working fluids can be purchased from the American National Institute of Standards and Technology (for example) who provide the NIST Reference Fluid Thermodynamic and Transport Properties (REFPROP) database [35]. The REFPROP database is actually a program which uses accurate equations for the thermodynamic and transport properties to calculate the state points of the fluid or mixture, and it can be linked to external programs such as Python and Matlab.

4. Renewable Energy Systems Coupling

The different energy technologies described in chapter 3 can be assembled and combined in a larger system according to demand characteristics. The main strategy is to extend the energy generating equipment with a storage technology in order to better match supply and demand and to improve the overall system efficiency.

Solar thermal collectors (described in section 3.2) and solar concentrators (described in section 3.3) are usually accompanied by hot water storage (described in section 3.4). The schematic representation of such a system is presented in Figure 35. Water heated by solar radiation is delivered to a hot water storage tank instead of being directly connected to the demand side. The demand side is also connected to the hot water storage tank and it is equipped with a three port valve to control the temperature of the supply hot water. Tank capacity is driven by the demand characteristics and size of solar collector (or concentrator) field. Solar concentrators and solar thermal collectors can share a hot water storage tank, however this is not the case when they operate at different temperature regimes. When the system is extended by an absorption chiller connected to the demand side of the hot water storage tank, it is called solar cooling system as described in section 3.6.

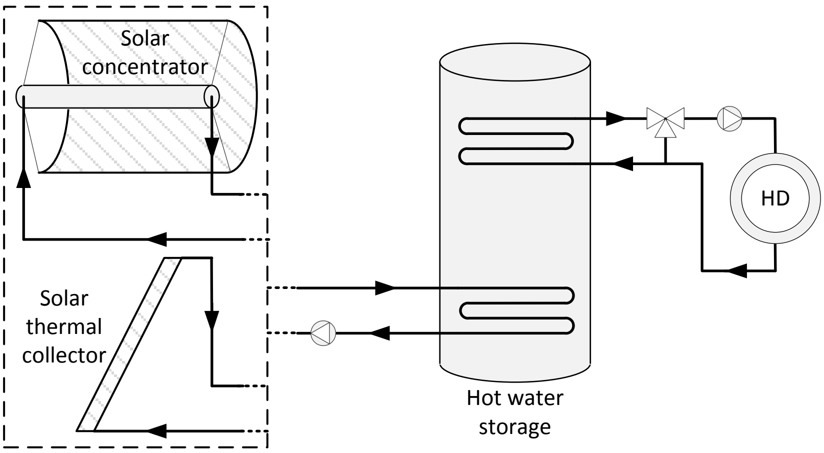

FIGURE 35 SOLAR THERMAL + HOT WATER STORAGE

Electricity generated on site is usually consumed by the facility's electrical appliances while the excess electricity is exported to the national grid. The alternative is to store the excess electricity in batteries and to consume it when there is a suitable electricity demand within the facility. Figure 36 graphically represents such an installation, with battery storage inserted between on-site electricity generating equipment (ORC and PV are of particular interest for REEMAIN) and a consumer within an industrial facility. While PV converts solar radiation into electricity, an ORC system is usually driven by waste heat from the facility. One of the partners in REEMAIN, SCM foundry, has the potential for generating electricity from a waste heat by utilising an ORC system. However the furnace process, which generates a significant amount of high grade waste heat, does not operate continuously and can be categorised as a batch process. Although a large amount of a waste heat is available, it is intermittent, so it is worth considering the installation of a heat storage system between the waste heat source (exhaust combustion gases) and an ORC system. This approach offers the opportunity to install a smaller ORC unit, hence reducing equipment capital cost.

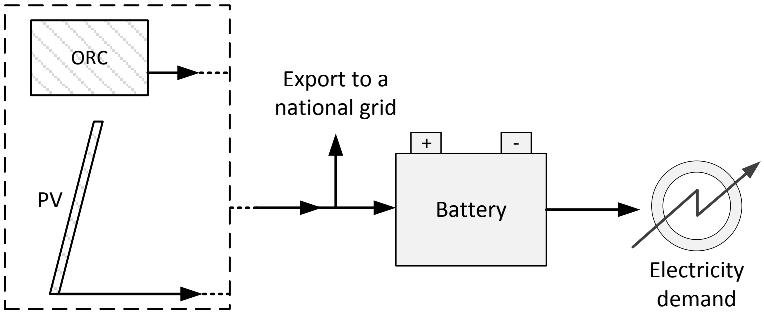

FIGURE 36 ELECTRICITY GENERATION + BATTERY STORAGE

Excess electricity generated on site, particularly from PV, can also be stored in the form of thermal energy instead of storing electrical energy in batteries or exporting to the grid. Figure 37 shows an example of a typical installation in which the electricity generated by a PV plant is converted to thermal energy in an electric water heater. Thermal energy can be consumed immediately if there is a heating demand or it can be stored in a tank to be used when needed. Nevertheless, despite the additional benefit that may be gained by extending a PV plant with an electric water heater; its main purpose should be to meet some of a facility's electricity demand rather than its heating demand.

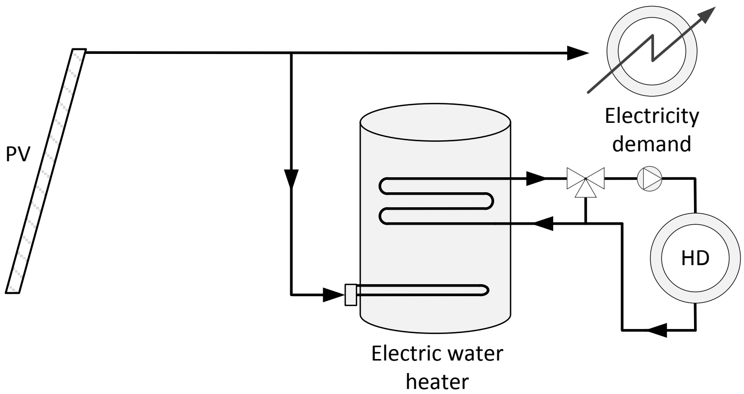

FIGURE 37 PV + ELECTRIC WATER HEATER

A tri-generation system (combined heating, power and cooling) can also benefit from storage technologies, whether heat, electricity or both. Figure 38 shows a tri-generation system (described in section 3.7) extended with both electricity storage (batteries) and thermal storage (hot water storage). Electricity generated in a micro-turbine is either consumed immediately in the facility or stored in batteries for later use also in the facility. Export to the grid is reduced to a minimum or completely avoided. Heat recovered from the micro-turbine exhaust gases is captured in a hot water storage tank instead of being used directly to drive an absorption chiller or to respond to a facility's heating demand. This offers the opportunity for better utilisation of the energy carried by the micro-turbine exhaust gases.

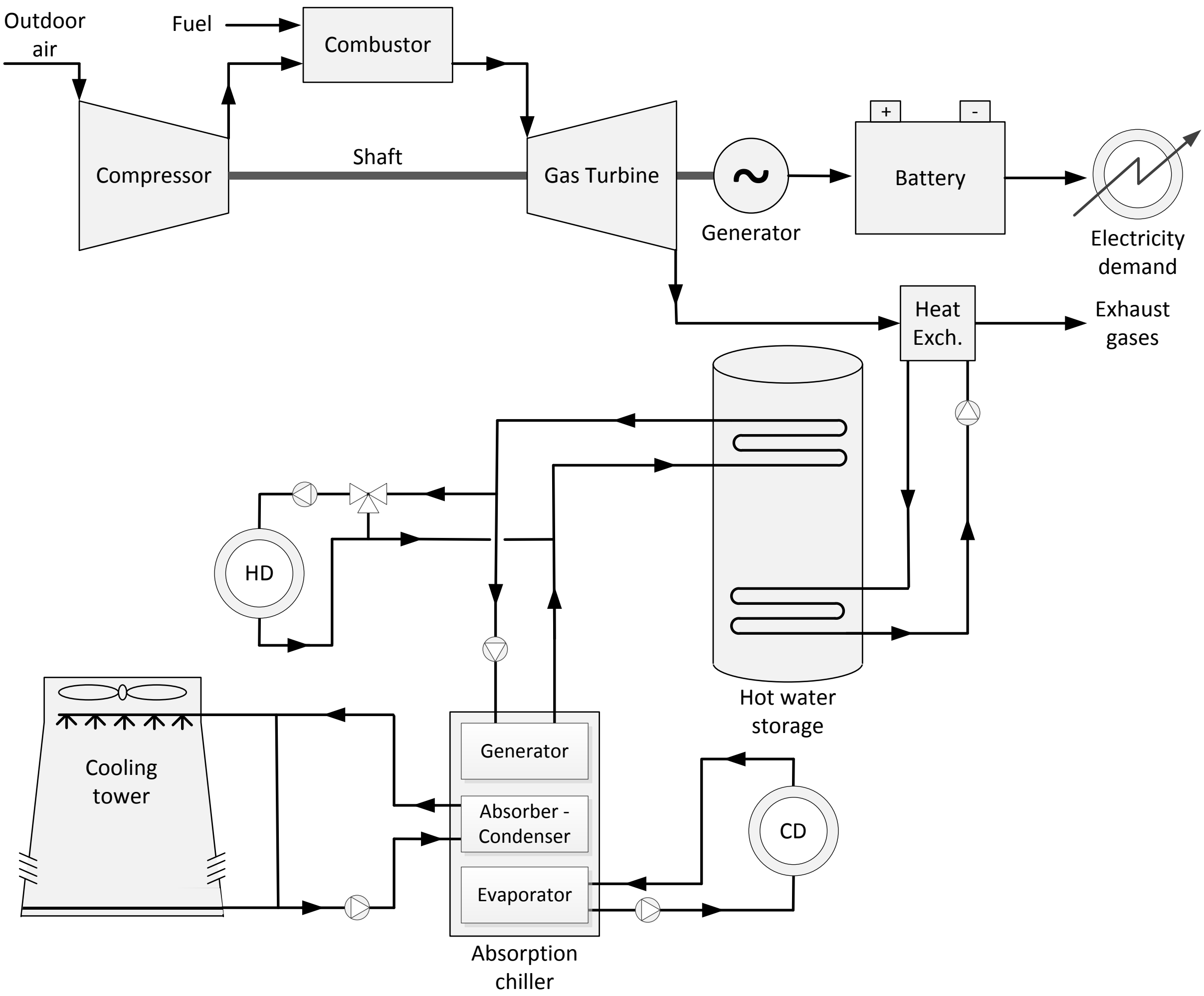

FIGURE 38 CHPC + HOT WATER STORAGE + BATTERY STORAGE

The complexity can be further increased by coupling these systems. For example, a solar cooling system can be built alongside with a PV plant equipped with battery storage. These two systems can be operated (hence analysed) independently or as a single system.

It is also important to mention that no matter which system coupling is selected as the most appropriate upgrade solution, the backup systems, particularly for providing heating and cooling energy, have to be present. The primary reason for this is to avoid the exposure of the manufacturing process to a relatively novel (and potentially unreliable) energy system, which within REEMAIN is highly dependent on environmental conditions.

5. Modelling Tools

One of the main tasks in work package 4 is to model the coupling of sustainable technologies and/or renewable technologies with industrial facility energy demands. The performance of various technologies, when coupled with energy demand, can be evaluated by system modelling. There are various system modelling tools available. They differ in complexity, input requirements, interoperability, cost, etc. The level of tool complexity is usually linked to the scale of problem addressed in a particular tool, while input requirements often directly correlate with tool complexity. Interoperability is a very important feature which is not always available in such tools. It is particularly useful for REEMAIN's WP4 since there is no single tool available which can be used for all system/plant modelling and optimisation. Most likely, various tools will need to be linked together, with different analyses conducted using different tools, in order to fulfil the aims of this work package. Interoperability leads directly to the need for data exchange between various tools. Tools which are planned to be used for system and plant modelling in WP4 are listed here with their main features and characteristics described concisely.

In principal, four types of tools have been identified as suitable for activities planned in WP4:

- Supply side (system) modelling tools,
- Tools for developing new component models,
- Demand side (plant) modelling tools, and
- Data exchange/processing tools.

5.1 Supply Side (System) Modelling Tools

Modelling energy systems has been studied for decades and many tools have been developed. We identified three the most advanced ones: IES-VE, EnergyPlus, and TRNSYS.

5.1.1 IES-VE

Virtual Environment by Integrated Environmental Solutions (IES-VE [36]) is a modern example of whole building/system dynamic energy simulation software. It is composed from multiple modules which allow users to investigate the performance of a building and associated energy systems.

The individual modules include climate, geometric modelling, solar shading, energy and carbon, lighting, airflow, HVAC, value/cost and egress modules that are linked by a single Integrated Data Model (IDM) through a Common User Interface (CUI) and allows data to be easily exchanged between the different applications. The integration of all of these modules means all aspects of a building's construction, location, geometry; climate, usage, systems and thermal performance can be modelled, and in turn, simulated. The IES-VE Main Modules are shown in Figure 39.

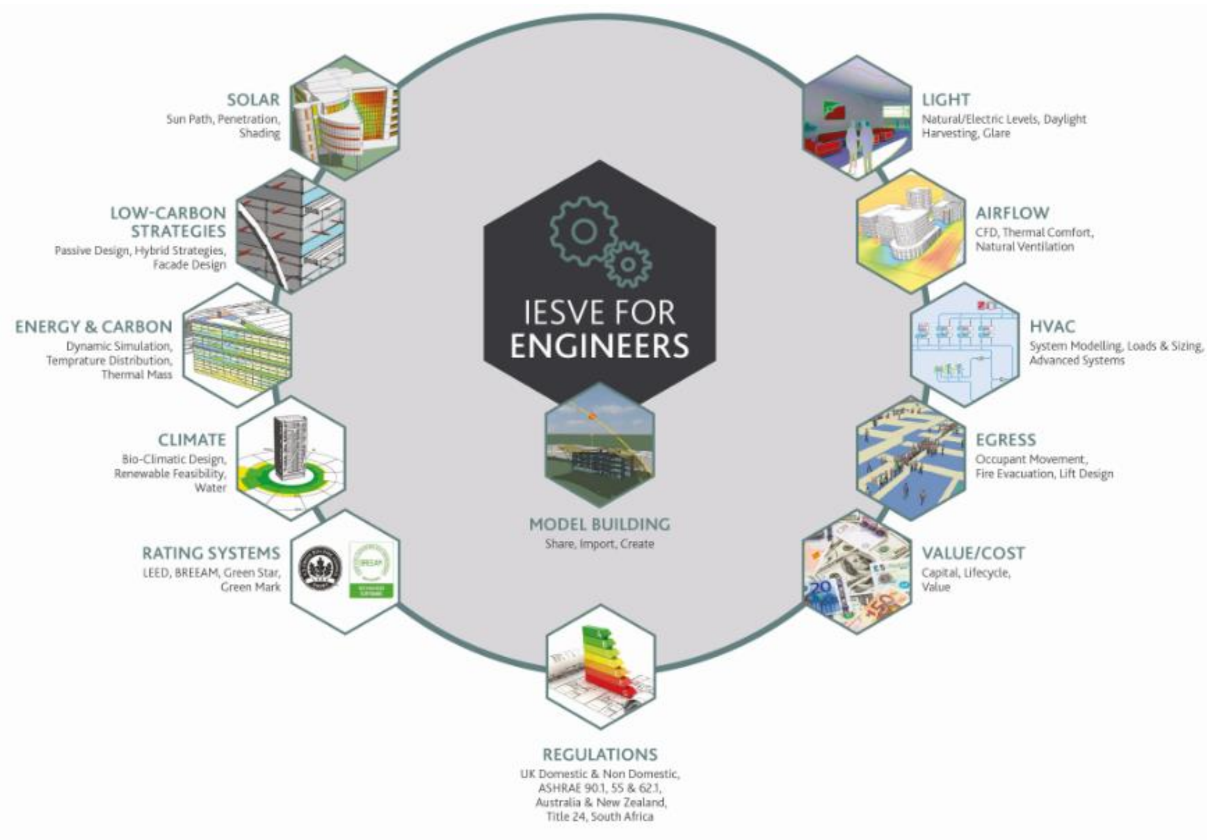

FIGURE 39 IES <VE> MAIN MODULES OVERVIEW

The physics behind a building and system modelling is hidden behind the CUI which means that the user provides software specific inputs and receives calculated outputs graphically. However, this does not mean that the knowledge of building physics and energy systems is not required. In matter of fact, it is quite opposite. The deep understanding of physics behind a building and system modelling essentially helps a user to interpret simulation results.

The primary energy and systems modules are detailed as follows:

ApacheSim is a dynamic thermal simulation module based on first-principles mathematical modelling of the heat transfer processes occurring in and around a building. ApacheSim qualifies as a Dynamic Model in the CIBSE system of model classification, and exceeds the requirements of such a model in many areas. The module provides an environment for the detailed evaluation of building and system designs, allowing them to be optimised with regard to comfort criteria and energy use. Within ApacheSim, conduction, convection and radiation heat transfer processes for each element of the building fabric are individually modelled and integrated with models of room heat gains, air exchanges and plant. The simulation is driven by real weather data and may cover any period from a day to a year. The time-evolution of the building's thermal conditions is traced at intervals as small as one minute. The simulation engine has the following features:

- Finite difference dynamic heat conduction modelling
- Dynamically calculated surface convection characteristics

- Air temperature, surface temperature and room humidity modelling
- Advanced solar and long-wave radiation exchange models
- External solar shading using data from SunCast
- Solar tracking through an arbitrary number of transparent internal partitions using data from SunCast
- Angle-dependent glazing transmission, reflection and absorption characteristics
- Accurate accounting for the radiant/convective characteristics of casual gains and plant heat inputs
- Room plant and control models allowing for limited heating or cooling capacity
- Simultaneous solution of sensible and latent heat balance equations for the whole building
- Optional integration with natural ventilation air flow simulation (MacroFlo) or HVAC system simulation (ApacheHVAC)
- Simultaneous integration with both MacroFlo and ApacheHVAC for the simulation of mixed-mode systems

Results output by ApacheSim include:

- Comfort statistics
- Energy consumption data
- CO2 emission data
- Room load statistics
- Plant sizes
- Detailed performance measures including hourly room temperatures (air, mean radiant and dry resultant), humidity, plant loads, casual gains and air exchanges
- Surface temperatures for comfort studies or CFD boundary conditions

ApacheHVAC simulates the performance of heating, ventilation and air conditioning systems. It links dynamically to the building simulation program ApacheSim, and optionally to MacroFlo. ApacheHVAC extends the capabilities of ApacheSim by providing a detailed representation of room heating and cooling units, air handling systems, central plant components and controls. These capabilities give the user a means of accurately assessing issues such as:

- Control operation and its impact on comfort performance
- Energy use
- Fresh air loads
- Free cooling
- Heat recovery
- Component sizing

- Sizing of mechanical air flows
- System psychometrics
- Distribution efficiency
- Boiler and chiller performance
- Fan and pump energy
- Mixed-mode operation

This module generates an extensive range of outputs. At the detailed level it is possible to trace individual psychometric and control processes occurring within a system. At the opposite extreme the program can supply aggregated monthly energy loads and consumption totals, optionally broken down by fuel or component type.

5.1.2 ENERGYPLUS

EnergyPlus [37] is a whole building energy simulation program used by engineers, architects, and researchers to model building energy consumption. It has been developed by the US Department of Energy (DoE). EnergyPlus is dynamic simulation software with powerful capabilities, an excellent reputation and free access. It is also open source, which means that anyone may obtain EnergyPlus source code, **modify it**, combine it with other software that is licensed under different terms, distribute it, and re-license it. Although relatively new, the first version was released in April 2001, EnergyPlus has its roots in two programs developed and released in the late 1970s and early 1980s, BLAST and DOE-2. Like its predecessors, EnergyPlus is an energy analysis and thermal load simulation program. Based on the most popular features and capabilities of BLAST and DOE-2 and extended with many new program modules, it calculates the heating and cooling demands necessary to maintain desired indoor thermal conditions, secondary HVAC system parameters and coil loads, as well as the energy consumption of primary plant equipment. The list of EnergyPlus features is quite long, but some of the most important are:

- Integrated, simultaneous solution,
- Heat balance based solution technique for building thermal loads,
- Combined heat and mass transfer model,
- Loop based configurable HVAC systems, etc.

EnergyPlus itself does not offer a user interface. It is a simulation engine for which inputs (and outputs) are simple ASCII text. This allowed a range of GUI programs to be developed; some of them commercially available (DesignBuilder [38], Sefaira [39], and Bentley's Hevacomp [40] and AECOsim Energy Simulator [41]) while others are free (OpenStudio [42] and Simergy [43]). The text base input/output files structure makes EnergyPlus highly interoperable which is of crucial importance for REEMAIN's work package 4.

5.1.3 TRNSYS

TRNSYS (TRaNsient SYstem Simulation) [44] is a dynamic building energy and energy supply systems modelling tool which has been used for more than 35 years for HVAC analysis and sizing, electric power simulation, solar design, building thermal performance, control analysis, etc. It comprises a graphical interface, a simulation engine, and a library of components. Components are individual systems (including various building models, HVAC equipment and renewable energy systems) defined by a set of inputs, outputs, and mathematical functions which describe their operation. The user is able to design a complex system by linking individual components to each other through the connection of inputs and outputs. Due to this modular approach, TRNSYS is capable of modelling a variety of systems at different level of complexity while the user has full flexibility to design and evaluate unconventional energy systems as well. This is TRNSYS's clear advantage over IES-VE and EnergyPlus. In addition to this flexibility, TRNSYS also provides a method for creating new components that do not exist in the standard package as well as supplying the source code and comprehensive documentation which helps the user to modify/add components not included in the standard library. Moreover, TRNSYS also links well with other simulation packages such as Matlab and Engineering Equation Solver (EES).

5.2 Tools For Developing New Component Models

Most of the technologies chosen for evaluation in REEMAIN have been included in previously mentioned simulation platforms. However, some of them are not covered and (simplified) models of them have to be developed in order to fulfil the tasks in WP4. There are two approaches in developing new models. The first requires the development of a model and its integration directly into a simulation tool. Both EnergyPlus and TRNSYS allow this. In the case of TRNSYS, it would be required to develop a new Type (model to be written in Fortran) and to integrate it in the software. The procedure to integrate a new model in EnergyPlus is very similar. The model developer has to write a program in C++ (in the latest version of EnergyPlus) or in Fortran (earlier versions), then to implement it in the EnergyPlus code. Before being usable, the customised EnergyPlus version has to be recompiled. In the case of IES-VE, the integration of a new model is more complex since it cannot be done without the involvement of IES developers. Being a closed-source proprietary tool, IES-VE accepts only in-house development of new components and software extensions, which process is defined by their internal development procedures. One of the tasks in WP3 is to develop a new component (a model of the organic Rankine cycle) and to integrate it within IES. DMU will work together with IES to achieve this. The other possible way to create and employ a new model is to develop it in a third-party application and link it to system simulation tools, such as EnergyPlus or TRNSYS, which allow data exchange with third-party applications. This is the approach which will be used for developing models of missing technologies in WP4. Two suitable programs have been identified for this purpose - Matlab and EES.

5.2.1 MATLAB

Matlab [45] is a high-level language and interactive environment used for numerical computation, visualization, and programming. It is an established platform for data analysis, for algorithm development, and for model and application creation. It also provides useful functions (through additional toolboxes) for solving and manipulating symbolic mathematical expressions. This allows the solution of equations analytically which is particularly useful in the development of energy models. An additional package, Simulink [46], provides a graphical environment for multi-domain simulation and model-based design. It is equipped with customizable block libraries and solvers for modelling and simulation of dynamic systems. In addition to these features, Matlab is also highly interoperable and allows interfacing with a range of other programs and programming languages such as C, C++, Java, Fortran and Python.

5.2.2 EES

Engineering Equation Solver (EES) [47] is a general equation-solving program which can numerically solve thousands of coupled equations including differential and integral equations and equations with complex variables. In addition, it can do optimization, provide uncertainty analysis, and perform linear and non-linear regression. ESS automatically identifies and groups equations which have to be simultaneously solved, ensuring that the solver always operates at optimum efficiency. The interoperability of ESS is also advanced, allowing user-written external functions and procedures, written in languages such as Pascal, C or Fortran, to be linked into EES. The major advantage of EES, in our opinion, is the comprehensive database of highly-accurate thermophysical properties of hundreds of fluids including organic refrigerants, ammonia, methane, carbon dioxide and many other real fluids, ideal gases, and brines. Such integrated functions are extremely useful for engineering calculations. The modelling of an ORC would not be possible without access to the thermophysical properties of various refrigerants, which places EES at the top of our list of tools for developing a simplified ORC model.

5.3 Demand Side (Plant) Modelling Tools

As already mentioned earlier, obtaining a facility's energy demand profiles is crucial for modelling the performance of proposed primary energy systems, including RES. In addition, energy demand profiles are required for proper sizing of these systems. Demand profiles can be obtained by monitoring or modelling. Two modelling approaches are considered for this work package. The first approach is to apply rough-cut modelling which has been developed by IES-VE in WP3. WP4 therefore provides an ideal opportunity to test the rough-cut modelling methodology. The second approach is to generate demand profiles in Siemens's Plant Simulation software which is an industry standard for modelling production systems and their processes.

5.3.1 IES-VE ROUGH-CUT MODELLING

The main aim of the IES-VE rough-cut modelling tool is to develop more detailed facility's energy consumption profiles (preferably at hourly intervals) from available low-resolution data such as monthly or annual utility bills.

The rough-cut methodology is deployed via a web interface which facilitates collaborative effort and also allows for easy integration with real-time data when it becomes available. First a utility bill or set of utility bills is attached to the project. Figure 40 shows a daily gas bill attached to the web platform. This can be daily, weekly or annual.

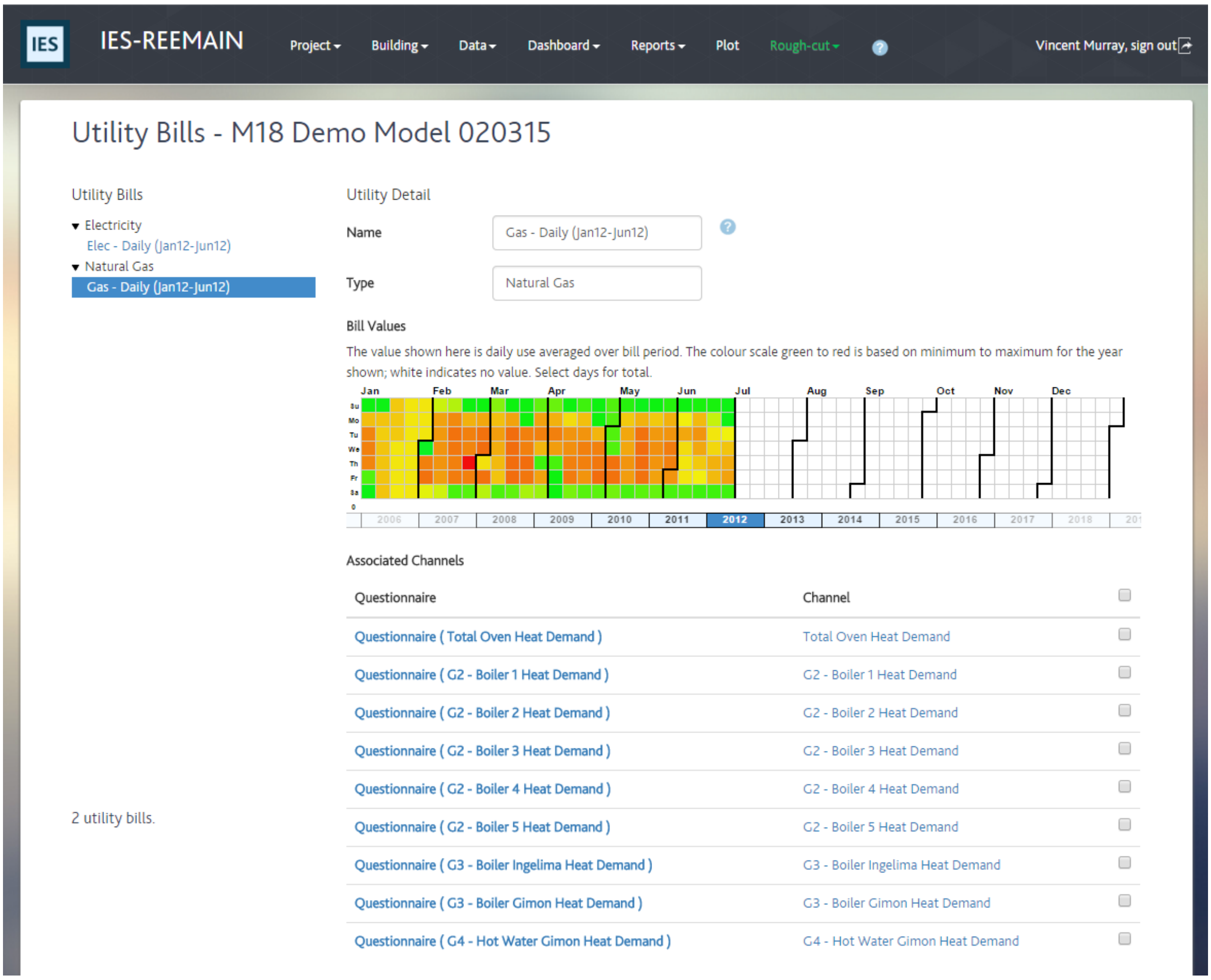

FIGURE 40 UTILITY BILL AND ASSOCIATED ROUGH-CUT DATA CHANNELS IN THE WEB PLATFORM

The tool then allows users to define the performance of each piece of equipment (called components in IES-VE modelling) attached to the utility bill. This can be done in the following ways:

- Manual creation of profiles – experienced users
- Use of standardised profiles from industry e.g. NCM in the UK
- Provide answers to a questionnaire – less experienced users

Next a rough-cut data channel is automatically created for each component and is connected to the utility bill. This hardwires relationships between the bill and the components as well as between each individual component. This means that as new information becomes available, either in the form of an updated bill or as performance information, it simply filters down to update the resulting rough-cut data channel automatically.

These data channels are then attached to their associated 3D components in the IES-VE model. A simulation is preformed and the results are analysed using the existing tactics and attitudes framework within the IES-VE or is used to estimate the likely impact of REEMAIN technologies.

The rough cut modelling tool is under development and will be described in detail in Deliverable D3.4 to be issued by the end of May.

5.3.2 SIEMENS PLANT SIMULATION WITH ENIBRIC

In order to generate demand profiles for individual suppliers or an entire production system using eniBRIC, the user has to start by modelling the material flow on a suitable level of abstraction in Plant Simulation. Typically, the smallest element of the simulation is a station or facility which has its own programmable logic controller or an individual workstation. However, multiple of these may be considered as just one element in a simulation model, e.g. a production line of multiple machines, a specific production area, an entire shop floor or even an entire factory building. Once a material flow model has been created, all elements will be extended with eniBRIC and parameterised. Furthermore, additional energy and media supplier instances of eniBRIC have to be added to the model in a similar manner. Additionally, some kind of superior process control needs to be implemented which is responsible for switching the individual eniBRIC instances (i.e. model elements) into the correct operating state at each point of time in the simulation. This can entail pause- or free-shift-shutdown as well as more complex control strategies.

During simulation, the individual instances will switch between operating states (either triggered by incoming parts to be processed or by the process control) while always reporting their demand to a previously defined supplier and to a central evaluation module. The information provided by the demanding elements (i.e. the current power demand etc.) is then accumulated over all elements and logged whenever a change occurs, effectively creating the demand profile. An example of this is depicted in Figure 41. In the specific example, material flow elements 3 and 4 always use the same amount of energy (flat line) while 1 and 2 differs (multiple levels) so that the sum calculated for supplier elements 1 and 2 individual equals the one calculated for the evaluation module.

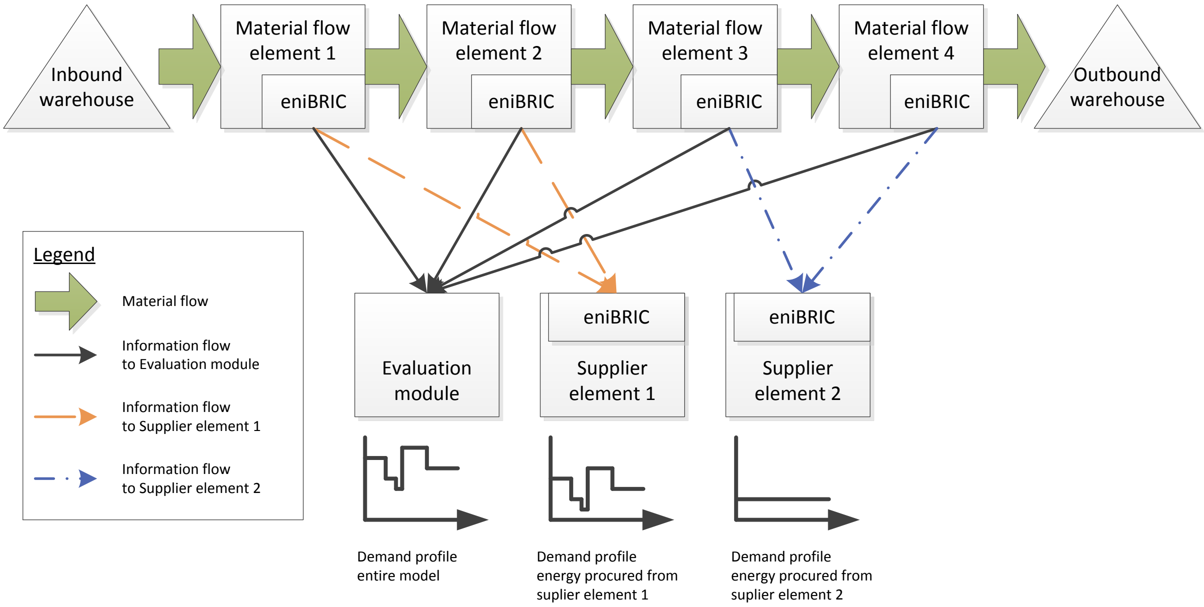

FIGURE 41 EXEMPLARY DEMAND PROFILE CREATION USING PLANT SIMULATION AND ENIBRIC.

5.4 Data Exchange/Processing Tools

The modelling activities proposed in WP4 are not linked to a single tool. We plan to use multiple tools, often in parallel, so-called co-simulation. In order to make co-simulation work, data must be exchanged between various tools. A typical example is data exchange between demand modelling tools and energy system modelling tools. The outputs from a demand modelling tool, such as Plant Simulation, are used as inputs for the energy system modelling. This is a fairly straight-forward task which gets more complex when system simulation outputs have to be passed back to demand modelling tool as inputs either for the next simulation step or for adjusting the parameters of a current simulation step. Data exchange is essential for simulation runs to converge upon a solution.

Another required feature is parametrisation and optimisation. Selected technologies for evaluation can be combined in various systems. In addition their size can vary and this affects overall performance. Where the number of parameters is small, the number of simulations needed is relatively small and these can be conducted manually. However, with an increased number of parameters the number of simulations can grow exponentially which requires an automated tool for preparing and passing parameter values to models. If the number of possible scenarios increases significantly, then the parameter study becomes impractical, since it would require excessive computing time. This is a type of problem for which optimisation techniques can help to find a nearly optimal solution by evaluating only a small number of possible scenarios from a large simulation space.

The final tool to be considered is a data processing tool. Performing a large number of simulations will result in a large number of outputs which often have to be post-processed before analysis. Post-processing and analysis include filtering and grouping, statistical analysis, charting, etc. Data processing also includes pre-processing. Collection of various data, such as energy consumption, temperatures and flow rates, is within the scope of REEMAIN and among the planned activities in several work packages (WP2 and WP5). Collected data will most likely have to be cleared, filtered, evaluated, and prepared for further use in both simulations and analysis, which also requires using some of data processing tools.

5.4.1 BCVTB

Building Controls Virtual Test Bed (BCVTB) [48] is a software environment which allows coupling of different simulation programs for co-simulation. For example, energy demand and part of the energy generating system can be simulated in EnergyPlus, while another part of the energy generating system can be simulated in TRNSYS and control and operations of the system can be defined in Matlab/Simulink. BCVTB allows data exchange between these tools as they simulate. Typical applications of BCVTB include performance evaluation of integrated energy and controls systems, development and testing of new control algorithms, modelling of innovative systems and controls which are not included in already available simulation programs, etc.

5.4.2 JEPLUS/JEPLUS+EA

The jEPlus [49] set of tools includes jEPlus for parametric simulations and jEPlus+EA for optimisation studies. JEPlus is designed to set up and manage parametric simulations with EnergyPlus while the results are collected in CSV tables. It also supports parametric simulations with TRNSYS. Flexible syntax allows specifying alternative values, including importing them from files, and random sampling from specified probabilistic density functions, including Gaussian, uniform, triangular and discrete distributions. In addition, random sampling of simulation jobs as well as Latin Hypercube sampling is supported. Simulation results post-processing can be automatically done since jEPlus allows running Python scripts in the data collection process.

jEPlus+EA is built on top of the jEPlus to allow the application of an optimisation algorithm to a parametric study. Executing all possible options of the parametric project guarantees finding the best solutions, however, when the parametric project is large this often becomes impossible due to lack of computing capabilities and/or time. jEPlus+EA is design to remove this barrier by applying the widely used and highly efficient multi-objective optimisation algorithm NSGA-II. Although it is created to be simple to use and to hide optimisation complexity, the user still has a flexibility to control the population size, crossover rate and mutation rate. Scatter plot and frequency histograms help the user to locate and inspect individual solutions as well as to visualise a distribution of parameter values within optimum solutions.

5.4.3 PYTHON

Manipulating with large datasets and doing pre-/post-processing can be a complex task which can be eased by using a programming language instead of an off-the-shelf tool such as MS Excel. Python [50] has been proposed as a suitable solution for such tasks since it is a widely used general-purpose, interpreted, interactive, and object-oriented programming language which gained popularity due to its very clear syntax and code readability. Clear syntax often allows programmers to write programs in fewer lines compared to similar programming languages such as Java or C++. One of the main advantages of Python is its comprehensive database of libraries which provides many tools for completing various programming tasks. For example, libraries such as NumPy, SciPy and Matplotlib allow the effective use of Python in scientific computing, while the Pandas library brings a high-performance tool for data manipulation and analysis. Another important feature of Python is that it is open source which allows its free use even for commercial applications.

6. Modelling Approach

This section presents our preliminary thoughts on a modelling approach which can be applied to the remaining WP4 tasks. The main aim of modelling is to identify the most suitable set of advanced energy generating systems (including renewable technology) which can partially or fully replace conventional energy generating systems in response to industrial facility energy demands, including heating, cooling and electricity, within a particular climate. Suitable energy generating systems have been selected from a comprehensive review of available technologies conducted in Task 3.1. These systems are a core element and a basis for the modelling approach described here. Simulation of system performance will be done in some of simulation tools described earlier in Chapter 5 such as EnergyPlus, IES-VE, TRNSYS, EES and Matlab.

In order to be able to conduct modelling, a facility's energy demand profiles (electricity, heating and cooling) have to be obtained. This can be done in three ways:

- by instrumentation and data collection as a part of the REEMAIN's work packages 2 and 5,
- by generating approximate profiles by applying rough-cut methodology developed and described in the REEMAIN's work package 3 – task 3.3, or
- by generating detailed energy profiles in a specialised tool such as Plant Simulation.

Regardless of the way energy demand profiles are obtained they need to have certain characteristics to be useful for the proposed modelling. Firstly, they have to be representative. This means they have to present typical facility operation by capturing energy consumption profiles as accurately as possible. Secondly, the frequency of energy demand profiles data has to be at least hourly in order to respond well to the energy generating systems dynamics. Last but not least, energy demand profiles should cover the whole year since the performance of some of selected energy generating systems is highly weather-dependant.

In addition to energy demand profiles, environmental parameters associated with the geographical location of an analysed facility have to be obtained. Outdoor temperature and humidity, solar radiation (direct and diffuse), wind speed and direction, among other environmental parameters, are crucial for proper evaluation of some of selected energy generating technologies. Historical weather data can be obtained from on-line services such as weather analytics [51] or white box technologies [52] which can be useful when modelling of energy generating systems is coupled to actual energy demand (collected by monitoring). However, using a single actual weather year should be avoided in energy simulations since no single year can represent the typical long-term weather patterns. This is very important since the outputs of energy modelling should result in a recommendation of which of the proposed systems can replace existing technology and provide satisfactory performance over a longer period of time than one year. We certainly do not want to base the decision on non-typical weather conditions, for example if the analysed year was particularly hot, cold or windy; since the modelling results should inform decision makers which energy system to choose and install. It is more suitable to use Test Reference Year-type (TRY) weather data which is composed statistically from measured data of representative months to form a whole representative year. The site's temperature, solar radiation and other parameters in TRY are more appropriate and result in a prediction of energy performance that is closer to the long-term average. There are several sources of TRYs such as ASHRAE [53] and CIBSE [54].

The first step in modelling should be the analysis of a facility's energy demand profiles, for two main reasons. The first is to enable adequate equipment sizing since equipment size affects both its performance and capital cost. The second reason is to determine the intensity of demand which means the operating time at a certain load during the year. This also affects the system sizing decision. System sizing is the second step and it can be done manually or as a part of the main analysis. If the system sizing is done manually as a step before the main modelling, then additional variability can be introduced by applying, for example, three system sizes. A small system can be sized to 20% of nominal capacity (nominal capacity is the capacity of the system which can cover maximum demand), a medium system can be sizes to 60% of nominal capacity, while a large system can be sized to full capacity. System sizing done based only on required capacity, without taking into consideration the intensity of a demand, can result in system operation at low load for the most of time which is usually inefficient.

The main step in modelling is coupling of energy demand with preselected energy generating systems, and performance simulation of these systems. There is at least one major challenge in coupling energy demand with energy generating systems which has to be overcome. Energy demand profiles generated by specialised process simulation tools are often discrete while system simulation requires time series data. Effort will be needed to overcome this issue by developing a procedure which converts discrete profiles into time-series with at least hourly frequency.

In cases where the system sizing has been done in a separate step we can apply “brute-force”, which means to simulate all possible scenarios, due to limited number of options. By executing all simulations the best solution can be manually picked by exploring simulation results and as a function of an assessment criterion. When the improved system responds to only one energy demand than the assessment criterion can be the reduction of energy purchased from the utility company (the rest of energy being produced on-site using the new system integrated in the existing plant). In cases where different energy demands are covered by the analysed systems, than we need to identify a proxy for assessing the impact of a reduction in consumption. The most common proxy is a carbon footprint which takes into account emissions from grid electricity as well as CO_2 produced by on-site fuel consumption.

On the other hand, if system sizing is a part of the main modelling, without the simplification of having three system sizes, than the number of possible scenarios can grow significantly which justifies the use of optimisation in order to find an optimal (or near optimal) solution. System size becomes one more parameter in the optimisation project. The potential objective of an optimisation study can be the overall reduction in CO_2 emissions. The optimisation project can be designed as a multi-objective problem where the second objective may be minimal payback period. In any case, the backup energy systems (at least for covering heating and cooling demands) have to be taken into consideration. Backup systems are often the existing systems which, due to the presence of new systems, will operate at reduced load for a longer period of time. This reduces the backup systems' overall performance and they become less efficient in comparison to their performance before the system upgrade.

Once the most suitable system upgrade is selected for a particular facility's energy demands, either as an output from the "brute-force" approach or from the optimisation project, further improvements can be made by adjusting the demand side. Demand profiles reflect typical facility operation, which is often driven by the need to fulfil production plans. If facility operation schedules can be adjusted, taking care to consider process limitations and without compromising production plans, then there is the potential for an energy generation system overall performance improvement. The ultimate goal is to reschedule a production process so the energy generating system can operate with the highest possible efficiency. An example of this is the use of solar energy generating technologies which are highly affected by environmental conditions. Increased production during midday can benefit from solar availability. Since part of energy generating systems are using energy storage, the opportunities for the process rescheduling increase greatly, which also leads toward the use of an optimisation process in order to find an optimal (or near optimal) process schedule to maximise the performance of the upgraded energy generating system.

Figure 42 summarises the proposed modelling approach. Energy requirements of various facility processes as well as technical building services (TBS) can be aggregated in energy demand profiles stored in a database. The database has to have records of a facility's location and environmental conditions. The existing energy generating systems (primary systems) have to be replaced/upgraded with more efficient and environmentally friendly systems. These systems can utilise renewable energy or/and the facility's waste heat energy. Coupling of energy demand profiles and proposed advanced systems in a modelling/optimisation study should result in the selection of the most suitable energy generating technologies to replace/support existing system within a particular climate conditions. Once the most suitable system upgrade is selected, its performance can be further improved by optimising the demand side through adjusting facility operation schedules.

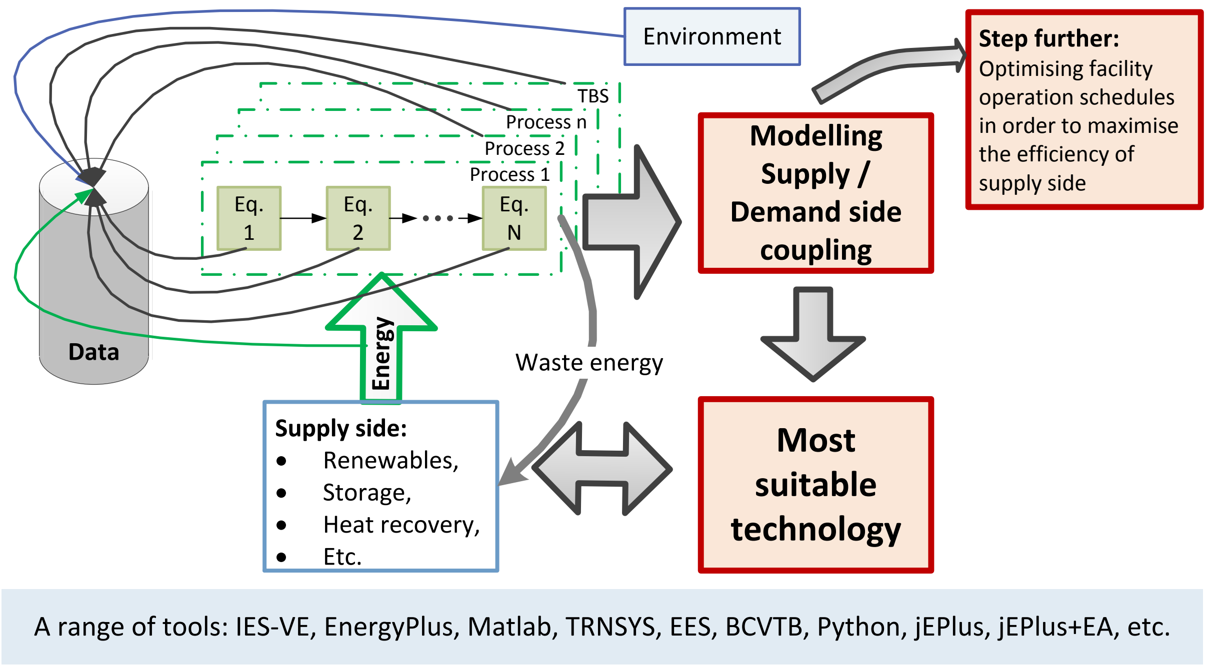

FIGURE 42 MODELLING APPROACH SCHEME

The modelling approach described above will help to identify the a more efficient energy generating system to meet the typical annual energy demand and then optimise the demand side to maximise the performance of an energy generating system. The alternative approach is to optimise the supply side, system sizing and demand side all at once. This is a more complex approach since there are more parameters in the optimisation study. However, the rationale for this approach is that different demand profiles (at the same geographical location) can have differences between the most suitable energy generating system type, arrangement and/or size. Allowing process rescheduling at the same optimisation step as a system selection/modelling should result in finding the best alternative energy generating system paired with an optimal process schedule which maximises system performance. This approach overcomes the potential disadvantage of the first modelling approach by eliminating the chance of selecting the best system for typical demand profiles while there might be some other system which offers improvements if demand profiles are rescheduled.

References

[1] J. Stoldt, E. Franz, A. Schlegel and M. Putz, "Resource Networks: Decentralised factory operation utilising renewable energy sources," *Procedia CIRP,* vol. 26, pp. 486-491, 2015.

[2] I. Pineda, S. Azau, J. Moccia and J. Wilkes, "Wind in Power: 2013 European statistics," The European Wind Energy Association (EWEA), 2014.

[3] Eurostat, "Share of renewable energy in gross final energy consumption up to 14% in 2012," [Online]. Available: http://ec.europa.eu/eurostat/documents/2995521/5181358/8-10032014-AP-EN.PDF/91350d4a-4b57-4833-b9f0-32cfe0a6d360?version=1.0. [Accessed 02 04 2015].

[4] F. Adamek, T. Aundrup, W. Glaunsinger, . M. Kleimaier, H. Landinger, M. Leuthold, B. Lunz, A. Moser, C. Pape, H. Pluntke, N. Rotering, D. U. Sauer, M. Sterner and W. Wellßow, "Energiespeicher für die Energiewende - Speicherungsbedarf und Auswirkungen auf das Übertragungsnetz für Szenarien bis 2050," VDE Verband der Elektrotechnik Elektronik Invormationstechnik e.V., Frankfurt am Main, 2012.

[5] T. Bocklisch, M. Böttiger and M. Paulitschke, "Multi-storage Hybrid System Approach and Experimental Investigations," *Energy Procedia,* vol. 46, pp. 186-193, 2014.

[6] B. Y. Ekren and O. Ekren, "Simulation based size optimization of a PV/wind hybrid energy conversion system with battery storage under various load and auxiliary energy conditions," *Applied Energy,* vol. 86, no. 9, pp. 1387-1394, 2009.

[7] J. M. Morales, A. J. Conejo, H. Madsen, P. Pinson and M. Zugno, "Facilitating Renewable Integration by Demand Response Demand response," in *Integrating Renewables in Electricity Markets*, International Series in Operations Research & Management Science Volume 205, 2014, pp. 289-329.

[8] H. Farhangi, "The path of the smart grid," *Power and Energy Magazine,* vol. 8, no. 1, pp. 18-28, 2010.

[9] P. Siano, "Demand response and smart grids - A survey," *Renewable and Sustainable Energy Reviews,* vol. 30, p. 461–478, 2014.

[10] B. Stahl, M. Taisch, A. Cannata, F. Müller, S. Thiede, C. Herrmann and A. Cataldo, "Combined Energy, Material and Building Simulation for Green Factory Planning," in *Proceedings of the 20th CIRP International Conference: Re-engineering Manufacturing for Sustainability*, Singapore, 2013.

[11] T. Creutznacher, R. Lepratti, S. Lamparter and G. Heinecke, "Performance Adaptive Manufacturing Processes in an Energy Efficient Car Production," in *Proceedings of the 11th*

Global Conference on Sustainable Manufacturing: Innovative Solutions, Berlin, 2013.

[12] N. Weinert, S. Chiotellis and G. Seliger, “Methodology for planning and operating energy-efficient production systems,” *CIRP Annals - Manufacturing Technology,* vol. 60, no. 1, pp. 41-44, 2011.

[13] F. Klocke, B. Döbbeler, M. Binder, R. Schlosser and D. Lung, “Ecological evaluation of main origins of consumption in manufacturing within the automotive sector,” in *Proceedings of the 10th Global Conference on Sustainable Manufacturing (GCSM)*, Istanbul;, 2012.

[14] M. Schenk, S. Wirth and E. Müller, Factory Planning Manual, Berlin Heidelberg: Springer-Verlag, 2010.

[15] M. M. Lankhorst, M. E. Iacob and H. Jonkers, Enterprise Architecture at Work - Modelling, Communication and Analysis, Berlin Heidelberg: Springer-Verlag, 2013.

[16] T. Langer, A. Schlegel, J. Stoldt and M. Putz, “A Model-based Approach to Energy-saving Manufacturing Control Strategies,” *Procedia CIRP,* vol. 15, pp. 123-128, 2014.

[17] A. Schreiber, A. Firlej, J. Stoldt, T. Langer and M. Putz, “Entscheidungsassistenz in komplexen Fertigungen mithilfe der "Linked Factory",” in *Vernetzt Planen und Produzieren VPP2013*, Chemnitz, 2013.

[18] M. Putz, J. Stoldt, C. Fanghänel, A. Bierer and A. Schlegel, “Making sustainability paradigms a part of PPC,” *Procidia CIRP LCE,* 2015.

[19] L. D. Danny Harvey, Energy Efficiency and the Demand for Energy Services, London: Earthscan, 2010.

[20] CIBSE, Guide B: Heating, Ventilating, Air Conditioning and Refrigeration, London: Chartered Institution of Building Services Engineers, 2005.

[21] J. Stoldt, A. Schlegel, E. Franz, T. Langer and M. Putz, “Generic Energy-Enhancement Module for Consumption Analysis of Manufacturing Processes in Discrete Event Simulation,” in *20th CIRP International Conference on Life Cycle Engineering*, Singapore, 2013.

[22] J. Eckstein, Detailed modelling of photovoltaic system components (MSc Thesis), University of Wisconsin, Madison, USA, 1990.

[23] D. L. King, “Photovoltaic Module and Array Performance Characterization Methods for All System Operating Conditions,” NREL/SNL Photovoltaics Program Review Meeting, New York City, NY, 1997.

[24] J. A. Duffie and W. A. Beckman, Solar Engineering of Thermal Processes, 4th ed., University of Wisconsin-Madison, USA: Wiley, 2013.

[25] ANSI/ASHRAE, "Standard 93-2010 (RA2014) Methods of Testing to Determine the Thermal Performance of Solar Collectors," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2014.

[26] ASHRAE, "Standard 96-1980 (RA 89) Methods of Testing to Determine the Thermal Performance of Unglazed Flat-Plate Liquid-Type Solar Collectors1989," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

[27] "Solar Rating and Certification Corporation," [Online]. Available: http://www.solar-rating.org/ratings/index.html. [Accessed 31 3 2015].

[28] BLAST, 3.0 Users Manual, Urbana-Champaign: Building Systems Laboratory, Department of Mechanical and Industrial Engineering, University of Illinois, 1999.

[29] ASHRAE, HVAC 1 Toolkit: A Toolkit for Primary HVAC System Energy Calculations, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1999.

[30] F. Merkel, Verduftungskuhlung, Berlin: VDI Forschungarbeiten, No 275, 1925.

[31] D. J. Benton, C. F. Bowman, M. Hydeman and P. Miller, "An Improved Cooling Tower Algorithm for the CoolToolsTM Simulation Model," *ASHRAE Transactions,* vol. 108, no. 1, pp. 760-768, 2002.

[32] York International Corporation, "YORKcalcTM Software, Chiller-Plant Energy-Estimating Program," 2002.

[33] J. Nouman, Comparative studies and analyses of working fluids for Organic Rankine Cycles - ORC (M.Sc. Thesis), Stockholm, Sweden: KTH Royal Institute of Technology, 2012.

[34] S. Quoilin, Sustainable energy conversion through the use of Organic Rankine Cycles for waste heat recovery and solar applications (PhD Thesis), Liege, Belgium: University of Liege, 2011.

[35] "REFPROP," [Online]. Available: http://www.nist.gov/srd/nist23.cfm. [Accessed 31 3 2015].

[36] "IES," [Online]. Available: http://www.iesve.com/. [Accessed 31 3 2015].

[37] "EnergyPlus," [Online]. Available: http://apps1.eere.energy.gov/buildings/energyplus/. [Accessed 31 3 2015].

[38] "DesignBuilder," [Online]. Available: http://www.designbuilder.co.uk/. [Accessed 31 3 2015].

[39] "Sefaira," [Online]. Available: http://sefaira.com/. [Accessed 31 3 2015].

[40] "Bentley Hevacomp," [Online]. Available: http://www.bentley.com/en-GB/Products/Hevacomp+Dynamic+Simulation/.

[41] "Bentley AECOsim," [Online]. Available: http://www.bentley.com/en-GB/Products/AECOsim+Energy+Simulator/. [Accessed 31 3 2015].

[42] "OpenStudio," [Online]. Available: https://www.openstudio.net/ . [Accessed 31 3 2015].

[43] "Simergy," [Online]. Available: http://simergy.lbl.gov/ . [Accessed 31 3 2015].

[44] "TRNSYS," [Online]. Available: http://www.trnsys.com/. [Accessed 31 3 2015].

[45] "Matlab," [Online]. Available: http://uk.mathworks.com/. [Accessed 31 3 2015].

[46] "Simulink," [Online]. Available: http://uk.mathworks.com/products/simulink/. [Accessed 31 3 2015].

[47] "EES," [Online]. Available: http://fchart.com/ees/. [Accessed 31 3 2015].

[48] "BCVTB," [Online]. Available: http://simulationresearch.lbl.gov/bcvtb. [Accessed 31 3 2015].

[49] "jEPlus," [Online]. Available: http://www.jeplus.org/. [Accessed 31 3 2015].

[50] "Python," [Online]. Available: https://www.python.org/. [Accessed 31 3 2015].

[51] "Weather Analytics," [Online]. Available: http://www.weatheranalytics.com/. [Accessed 31 3 2015].

[52] "White Box Technologies," [Online]. Available: http://weather.whiteboxtechnologies.com/. [Accessed 31 3 2015].

[53] "ASHRAE Weather," [Online]. Available: https://www.ashrae.org/resources--publications/bookstore/climate-data-center. [Accessed 31 3 2015].

[54] "CIBSE Weather," [Online]. Available: http://www.cibse.org/knowledge/cibse-guide/cibse-guide-j-weather,-solar-illuminance-data-(cd. [Accessed 31 3 2015].