WHY

D1.2

State of the art in policy driven and private-initiative interventions to foster the energy transition and Energy System Modelling

LEGAL DISCLAIMER

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Authors	Thomas Nacht (4ER) Robert Pratter (4ER) Johanna Ganglbauer (4ER) Corina Bolintineanu (RGI) Amanda Schibline (RGI) Armando Aguayo (UD)
Internal reviewers	Cruz E. Borges (UD)
External peer reviewers	Heike Brugger (ISI-FH). Pending.
Document approval	Cruz E. Borges (UD) Chris Merville (GOI) Andrzej Ceglarz (RGI) Panagiotis Fragkos (E3M)
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EXECUTIVE SUMMARY

The WHY Project follows the ambitious approach to improve the representation of household electricity demand in Energy System Models by applying a Causal Model to simulate the behaviour of residential consumers that leads to the consumption of electricity. Next to the Causal models, other models to represent energy systems of different scales, appliances within buildings, etc. need to be considered. In order to be able to create all the models making up the WHY Toolkit, research was conducted to identify suitable approaches to tackle the different modelling challenges, which can occur during the creation of the WHY Toolkit. In Deliverable D1.2 the results of the research conducted are presented. Not all the models or other aspects of residential energy consumption will be put into action in the WHY Toolkit. The results presented here are a pool of approaches of which the most relevant ones will be chosen and used further in the WHY project. The decision on which approaches will be chosen will be made in cooperation with the WHY Use Case Managers as part of Task T1.3. The results will be presented in Deliverable D1.3.

A major novelty of the WHY project is the consideration of people's reaction to external stimuli (intervention) and how these reactions translate to their energy consumption behaviour. In order to better classify and understand these external stimuli, we identified five following types/categories of policy instruments:

- Legislative and regulatory instruments
- Economic and fiscal instruments
- Agreement based or cooperative instruments
- Information and communication instruments
- Knowledge and innovation instruments

These policy instruments differ in how they aim to achieve a certain reaction in the policy targets. To get a better understanding of these instruments, the WHY consortium identified a multitude of national as well as international laws, initiatives, regulations, directives, etc. The purpose of this research was not to obtain an exhaustive list but rather to deepen the knowledge on how the instruments described above are applied in reality. Furthermore, the consortium differentiated between policy action with focus on energy, policy actions with focus on transport as well as business initiatives with focus on energy and business initiatives with focus on transport.

As for the policy actions with focus on energy, a total of 71 different actions from 6 different countries and 3 different international scales have been identified. Most of them are related to the sector of energy efficiency. Of these 71 actions, a total of 23 were legislative or regulatory actions and 21 co-operative instruments.

In the segment of policy actions with focus on transport, a total of 29 different actions have been identified. Most of them can be related to Spain (due to the origin of the consortium member conducting the research). The researched actions had a strong focus on sustainable mobility as well as pedestrian mobility and public transport strategies.

In contrast to the policy actions, business initiatives have economic benefits as targets and are developed and initiated by businesses rather than public authorities. For the section of

business initiatives with focus on energy, a total of 18 actions have been identified, whereas for the section with a focus on transport, only three actions were identified.

The research conducted provides the WHY consortium with a better understanding of the different interventions that will be relevant for the WHY Toolkit.

With the analysis of the actions concluded, the next phase was divided into two main parts: (1) Research on approaches for causal models and (2) research on models and approaches of relevance to the residential sector.

To better structure and classify the different approaches for causal models a taxonomy of the tasks that causal models should carry out is presented and the different libraries to implement causal models and several models have been assessed on these aspects.

Following the classification and research done for causal models, the next step was to research, analyse and classify the possibilities to address energy related aspects of residential buildings and their inhabitants. The different aspects to be considered are very heterogeneous, thus, no common approach in how to address and treat them could be identified.

The analysis of **models for different scales of energy systems** provided a deeper understanding of energy consumption (thermal or electric) in different settings. They often work as a framework where multiple different, more or less detailed models, are included and soft-linked. 10 different already existing models have been analysed and discussed towards their relevance to WHY. The large scale energy system models have been neglected as in the focus of this deliverable are residential buildings (as small scale energy systems) rather than entire countries (as large scale energy systems). This decision is supported by the fact that the large scale energy system models PRIMES and TIMES, to be used in the WHY project, are fixed by the WHY grant agreement[1].

In the WHY project the option of shifting loads or using certain loads at certains times is a potential option for residential consumers. But there are certain loads (**appliances**) that are not available for load shifting due to technical, user behavioural or comfort restrictions. Modelling these loads generally comes down to considering pre-defined load profiles which are applied once the device is activated.

Another important option that affects the energy consumption of residential users are energy efficiency approaches. For the purpose of the WHY Toolkit two main approaches to increase energy efficiency in the residential sector have been identified:

- Renovation measures of the building envelope including replacement or upgrade of windows and wall / roof thermal insulation
- Using appliances with better energy labels and higher energy efficiency

The latter can be represented in models by using new load profiles for non-flexible appliances or improved parameters in technical models of appliances that can be used flexibly. Simulating renovation measures, on the other hand, comes down to changing the technical parameters of buildings (e.g. the U-values of building shells). For this purpose a

[1] The large scale models are set by the GA and will be considered later during the project (see Deliverable D1.1)

substantial research of different parameters has been conducted. Different technical parameters for types of insulation, wall material, window types, etc. have been identified and described in detail in this deliverable.

In order to obtain more control over energy consumption and the behaviour of devices, residential consumers can make use of **energy management systems (EMS)**. There are a multitude of different options of EMSs available on the market, that differ in price, applicability and (management) options provided to the user. For this deliverable the WHY consortium provided examples of EMS for three different categories: (1) Open Source, (2) Research and (3) Commercial. The purpose of this research was to create an understanding of the options these EMS provide and thus deduct necessary code elements for the WHY Toolkit rather than obtaining actual code to be used in the WHY Toolkit.

One of the key options to make residential consumption more flexible is the use of **energy storage systems**. For this purpose the WHY consortium has identified a wide variety of technologies, from battery storage systems (and subtypes) over thermal storages to mechanical storages. Storage systems are modelled using mathematical equations but there are many different approaches for different technologies available. They differ in degree of detail and time required to solve the underlying equations. A total of 14 different approaches for 5 different storage types have been identified.

Apart from storage systems, there are certain types of devices that can be controlled by EMS to change their operational behaviour in order to meet certain goals. Amongst those, the **Heating Ventilation Air Conditioning Systems** (HVAC systems) and **Electric Vehicles (EV)** are the most relevant for the residential sector. On the one hand, for the HVAC systems different technologies are relevant, for which a multitude of different modelling approaches exist. This deliverable includes a summary of general approaches for the technologies, followed up by a set of libraries with commonly used models for these technologies. On the other hand, for the EV a review of different models approaches for modeling the mobility needs are presented and discussed. In particular Multi Agent Systems, Database models based on Weibull distributions are assessed.

One of the key changes to the energy system of the past years was the technological advancements in the sector of decentralised generation technologies. They provide residential consumers with the means to generate their own energy for self-consumption or other purposes. Investments in **Generation Technologies** are a key decision derived from the Causal Model and a key influencing factor when it comes to consumption behaviour, thus it is necessary to consider them in the models of the WHY Toolkit. The following technologies were deemed relevant for the residential sector: (1) PV/Solar generation, (2) Micro-Wind generation and (3) Combined Heat and Power generation (CHP). For the latter, the two different control strategies (electricity-led or heat led) and the different fuels (gas powered, biomass, or hydrogen) were considered. 9 different approaches to model these 3 types of generation technologies have been identified during the research.

The last relevant aspect considered during the work done in Task 1.2 are **business models** related to energy use in the residential sector. Formerly passive consumers (especially residential consumers) are slowly transitioning to becoming more active participants in the energy system, as suggested by the EU Climate Policy Package. As such new businesses are emerging, which aim at providing new services to residential consumers to generate profits for the businesses and benefits for the residential consumers. The research concluded by the WHY consortium identified the following most relevant business models to be considered in the WHY Toolkit:

- Energy as a Service
- Peer-to-Peer electricity Trading
- Aggregators
- Community-ownership models
- Pay-as-you-go models

As a conclusion, the Deliverable D1.2 provides an overview of the different aspects to be considered in the modelling tasks of the WHY project and should provide the reader with a general knowledge on different methodologies and approaches when trying to create a holistic representation of household energy consumption and the underlying decision processes. Finally, the decision on which modelling approaches to use in the further progress of the WHY project will be made during the WHY Use Case discussion in Task 1.3 and will be described in Deliverable D1.3.

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Long text
AC	Alternating Current
CFD	Computational Fluid Dynamics
DAG	Directed Acyclic Graph
DC	Direct Current
DR	Demand Response
EaaS	Energy as a Service
EMS	Energy Management Systems
ESCO	Energy Service Companies
ESM	Energy System Model
EV	Electric Vehicle
HVAC	Heating, Ventilation and Air Conditioning
ICE	Internal Combustion Engine
OCV	Open Circuit Voltage
P2P	Peer-to-peer
PAYG	Pay-as-you-go
POF	Potential Outcome Framework
PV	Photovoltaics
SCM	Structural Causal Models
SHGC	Solar Heat Gain Coefficient
SOC	State of Charge
VPP	Virtual Power Plant
VT	Visible Light Transmittance

1. Introduction

The project WHY aims at the development of the WHY Toolkit which facilitates a Causal Model in combination with technical models to provide a better and deeper understanding of electricity consumption in European households. The software will enable users to:

- make better forecasts for electricity consumption in households,
- analyse, evaluate, and validate policy decisions or other interventions such as changes in regulation, policy measures, funding, etc.,
- examine how today's world would look like if certain energy policy decisions had or had not been taken.

The WHY Toolkit has 2 main elements at its core, the Causal Model which sets a relation between a cause and a decision made by the inhabitants of residential buildings and the corresponding Technical Models which close the gap between decisions and behaviour of the inhabitants and the actual energy (electricity) consumption caused by the devices. While this is an oversimplification, it describes the overall structure of this Deliverable which contains the following chapters:

1. **Interventions for User Behaviour:**
   This chapter describes the results of the research phase aimed at identifying policy instruments and initiatives found in the energy sector in order to obtain the information required to define the interventions to be implemented in the Causal Model of the WHY Toolkit.
2. **Causal Models:**
   This section of Deliverable D1.2 provides a description of the research results on Causal Models, presenting the overall taxonomy of Causal Models as well as relevant modelling approaches which will be considered to be used in WHY.
3. **Technical models:**
   In the subsequent chapters, the Deliverable describes the different technical devices, appliances and aspects of household energy consumption considered in the WHY project. During the WHY-Project these devices, appliances and aspects need to be cast into mathematical models which allow their simulation. The chapter provides an overview of the different devices, appliances and aspects of household energy consumption with relevance for WHY and gives an overview of modelling approaches for these. The decision on which devices, appliances and aspects and which corresponding simulation models are to be considered in the WHY Toolkit will be made during the discussion with the WHY Use Case Representatives and described in Deliverable D1.3.

2. Interventions for User Behaviour

User behaviour is a complex issue, as it is influenced by a multitude of factors, including economic status, age, education, lifestyle, political environment and others (Gram-Hanssen et al., 2004), (Morley and Hazas, 2011). The WHY project aims to identify the possible user reactions and their effect on the energy consumption due to external stimuli. In the context of the WHY project, these external stimuli are called "interventions". In this chapter different approaches for policy driven interventions are discussed and presented.

2.1. Policy Instruments as foundation of interventions

One of the key purposes of the WHY project is to provide policy makers with a tool to better assess and analyse the results of their policies on the behaviour and decisions of residential inhabitants and, thus, household energy consumption. This will be achieved via interventions with which a Causal Model is fed in order to simulate the reaction of residential consumers. Understanding the nature of different policy instruments is essential to identify relevant interventions, which will serve to activate the Causal Models. Bouwma et al. (2015) distinguish among following policy instruments:

- **Legislative and regulatory instruments:**
  These instruments refer to binding requirements defined by a public authority and can be followed by sanctions in case of non-compliance. As a result the public authority uses its position of power to "force" an influence on the actor's behaviour.
  Such instruments have **advantages** such as: (1) Actors are forced to comply whether they want to or not, (2) all actors are affected equally and (3) they improve the predictability of the public authority's actions.
  However, they also show some **disadvantages** such as: (1) Costs to comply are paid by the involved actors, (2) limited coping abilities in complex dynamic situations and (3) change is not coming from the actors themselves but they are forced to comply, what in some cases can lead to a limited societal buy-in (and requiring control and enforcement by the authority).
- **Economic and fiscal instruments:**
  These instruments focus on providing financial boons outside the market such as loans, subsidies, taxes, etc. As these instruments most likely will be applied under market governance, they can be considered as having a voluntary character.
  The major **advantages** of economic and fiscal instruments are that (1) market failures can be corrected and (2) a functioning market could theoretically be created, but balancing the economic and fiscal instruments in that regard is quite a challenge.
  The **disadvantages** of those instruments are as follows: (1) in some cases they can generate additional costs due to the subsidies, (2) they cause additional efforts regarding the administrative aspects of loans and taxes (which may prevent some actors of applying), (3) regardless of the incentives, actors might still not comply due to internal reasons, thus resulting in limited effectiveness of the policy instruments and (4) there potentially will be a competition for the subsidies, funds, etc. among the actors, which could lead to additional administrative efforts and

possibly frustration with the actors. In addition, (5) it requires control to avoid misappropriation of subsidies.

- **Agreement based or cooperative instruments:**
  This instrument relies largely on voluntary cooperation between the government and the individual actors, as for example public-private-partnerships. Covenants or agreements define the rules to abide by.
  The big **advantage** of this instrument is that it relies solely on the voluntary contribution of individual actors, which indicates their motivation to comply. If that was not the case, the cooperation of the government, other public authorities and actors would not have been agreed upon in the first place.
  The **disadvantages** of those instruments encompass the following aspects:, (1) while the resistance to comply within the cooperation network will be very low, actors outside the network might not have an incentive to cooperate or might even oppose them, (2) not complying will very likely not have any consequences if no sanctions are agreed upon, (3) a precise distribution of responsibilities and tasks requires investing substantial resources, otherwise conflicts between involved actors may arise, (4) these instruments often lead to high costs for setting up the cooperation.
- **Information and Communication Instruments:**
  This instrument tries to influence the actor's behaviour by providing them with information on the topic at hand (one-directional communication). This can range from simple information to learning materials, etc.
  The main **advantage** of this instrument is the potential to provide the information to a large group of users.
  Due to the informational character of the instrument there are some **disadvantages** such as (1) that information does not necessarily lead to compliance and (2) that it will be quite challenging to reach actors, which are not interested in the project.
- **Knowledge and innovation instruments:**
  These instruments focus on a joint acquisition of knowledge through social learning. The knowledge gained acts both as information and as capacity to act accordingly. This instrument can be facilitated as Communities of Practice, Living Labs, etc.
  This instrument is **advantageous** as it allows the involved actors to contribute which lowers the resistance, furthermore it is flexible enough to cope with complex situations. Further **advantages** are (1) involved actors will very likely be highly motivated to participate and (2) through collaborative learning, the instrument might lead to new ideas which have a high chance of success.
  On the opposite side some **disadvantages** have to be considered, (1) the group of involved actors might be limited to a small group of frontrunners, which will only focus on providing benefits for their "small community", (2) this instrument requires a high degree of cooperation and identification with the cause of all involved actors, (3) this instrument often means high transaction costs due to its labor intensive character.

These identified policy instruments build the foundation of the interventions, which will be applied in the Causal Model.

2.2. Methodology for the research of policy instruments

To create a relatable and conclusive foundation for the Causal Model, the WHY-consortium applied the following approach:

1. A taxonomy for regulatory, legislative measures and industrial initiatives (defined in Section 2.1) was defined. The taxonomy includes the most relevant aspects from the project's point of view:
    a. **Type of Action:** Classification of the type of action, such as: Directive, Regulation, Ordinance Act, etc.
    b. **Main targeted policy area:** Classification of the scope, such as: Energy Efficiency, Renewable Energy, Load Shifting, etc.
    c. **Brief description** of the action and its intended goals
    d. **Time Horizon:** Timeframe under which these actions should be applied.
    e. **Geographical Scope:** Geographical coverage of the measure
    f. **Effects on household consumption:** Estimation of the effects that the measure will have on household consumption.
2. Each consortium member researched national and international regulatory or legislative measures or industrial initiatives according to their background, nationality and expertise. The focus of this approach was to identify different actions in each category of policy instrument. As there are a multitude of these actions and measures available, the list researched is not exhaustive, but rather provides an exemplary overview of the application of these instruments under different conditions.
3. The information provided by the consortium members was streamlined and brought into a final form, the results are presented on the Zenodo-Page of the WHY-project[2].
4. The researched list will act as a baseline for the identification of the interventions necessary for the Causal Model. The identification of these interventions is not part of this Deliverable, but will be presented in Deliverable D1.3 and will be part of the process of involving the stakeholders of the different WHY-Use Cases.

2.3. Results

This chapter presents a short summary of the results obtained during the research. For more detailed information please refer to the Zenodo-Page of the WHY-project where the entire table of results is presented.

2.3.1. Policy actions with focus on Energy

For the category "*Policy Actions with focus on Energy*" a total number of **71 different actions** was identified. Table 1 shows the distribution of these identified actions amongst the different types of instruments as described in Section 2.1. The category "Other" contains actions, which do not belong to any of the other specific types of instruments.

Table 1: Distribution "Policy Actions with focus on Energy" according to the type of instrument applied

[2] https://zenodo.org/communities/why/?page=1&size=20

Type of Instrument	Number
Legislative/regulatory instruments	23
Economic/fiscal instruments	9
Co-operative instruments	21
Information and communication instruments	13
Knowledge and innovation instruments	1
Other	4

Table 2 indicates which geographic scope the identified actions have. The majority of identified actions come from the EU wide legislation, Spain, Germany and Austria, which results from the contexts in which the Use Cases will be applied at the later stage of the project. Furthermore it needs to be stated again, that the list of actions researched is not exhaustive but rather exemplary.

Table 2: Distribution of "Policy Actions with focus on Energy" according to the geographic scope of the actions

Geographic Scope	Number
Global	3
Europe	18
Germany	13
Belgium	1
Austria	11
Spain	6
Bilbao (Spain)	18
Gipuzkoa (Spain)	1

Finally, Table 3 shows the distribution of the actions on the main targeted area. As can be seen from the results, there is a strong preference for actions in the area of "Energy Efficiency" followed by "Renewable Energies". A total of 19 different targeted areas have been identified in the process, which clearly shows the multitude of different actions applied.

Table 3: Distribution of "Policy Actions with focus on Energy" according to the main targeted area of the action

Main targeted area	Number
Achieve net-zero emissions	1
Black out	1
Combat climate change	1
Emission reduction	2
Energy and climate	1
Energy efficiency	39
Energy efficiency reward	1
Energy legislation	1
Energy savings in households	1

Energy taxes	1
Grid Operation	1
Improving economic viability of electricity system	1
Load shifting	1
Load shifting ("foment rational use of available resources")	1
Promote private investment in home PV	1
Renewable energies	4
Renewable energy	10
Sustainable development	1
Total energy efficiency in buildings	2

2.3.2. Policy Actions with focus on Transport

For the category "*Policy Instruments with focus on Transport*", a total of **29 different actions** were identified. It needs to be stated at this point that the actions with focus on Transport were provided by the Spanish consortium members, which explains the strong focus on Spanish actions. Table 4 shows the distribution of these identified actions amongst the different types of instruments as described in Section 2.1.

Table 4: Distribution of "Policy Actions with focus on Transport" according to the type of instrument applied

Type of Instrument	Number
Legislative/regulatory instruments	4
Economic/fiscal instruments	0
Co-operative instruments	21
Information and communication instruments	3
Knowledge and innovation instruments	0
Other	1

As can be seen in Table 4 there is a strong focus on Co-Operative Instruments, which is very interesting especially when compared with actions of the category "*Policy Instrument with focus on Energy*", where legislative and regulatory instruments played an equally important role. Since the numbers presented here are merely a glimpse of possible actions and most inputs derive from Spain, this result should not be overrated.

Table 5 shows the distribution according to the geographic scope of the actions. Since the actions were provided by the Spanish consortium members there naturally is a very strong, almost exclusive focus on actions from Spain.

Table 5: Distribution of "Policy Actions with focus on Transport" according to the geographic scope of the actions

Geographic Scope	Number
Global	1
Europe	3
Germany	0

Belgium	0
Austria	0
Spain	1
Bilbao (Spain)	24
Gipuzkoa (Spain)	0

The main targeted areas identified for the actions in the category "*Policy Instruments with focus on Transport*" differ greatly from those for the category "*Policy Instruments with focus on Energy*" which can be seen from the results in Table 6. A total of 10 different main targeted areas have been identified in the process.

Table 6: Distribution of "Policy Actions with focus on Transport" according to the main targeted area of the actions

Main targeted area	Number
Reduced emissions from vehicles	1
Reduced emissions from heavy-duty vehicles	1
Reduced emissions from transport	2
Sustainable mobility	8
Pedestrian mobility strategy	5
Public transport strategy	5
Cyclist mobility strategy	2
Strategy for private vehicle and parking	3
Environment strategy	1
Sustainable development	1

2.3.3. Business Initiatives with focus on Energy

An alternative to the Policy Actions are Business Initiatives which can also foster behavioural change but follow a different approach. Rather than trying to foster change in energy behaviour from an "authority's perspective", business initiatives see a business model which provides benefits to customers when they change or adapt their behaviour. Energy Service Companies (ESCOs) are a prime example of a type of company which would foster behavioural change through business initiatives.

Interestingly enough, the type of instruments applied to the policy actions can also be applied to the business initiatives, as can be seen in Table 7. For the purpose of research a total of 18 actions have been identified, mostly by the project partner GOIENER, in whose field of expertise are said business initiatives.

Obviously since Business Initiatives have no legally binding character, none of them can be categorised as "Legislative or regulatory instrument". The two main types found for these actions are co-operative instruments and information and communication instruments. It needs to be stated though that the initiatives identified are but a fraction of the multitude of business initiatives fostering behavioural change. Again the purpose of the research was not to create an exhaustive list of initiatives but rather provide an insight into the different possibilities.

Table 7: Distribution of "Business Initiatives with focus on Energy" according to the type of instrument applied

Type of Instrument	Number
Legislative/regulatory instruments	0
Economic/fiscal instruments	3
Co-operative instruments	7
Information and communication instruments	5
Knowledge and innovation instruments	2
Other	1

When it comes to the geographic distribution of the initiatives, almost half of the initiatives are from the city of Bilbao in Spain, which lies within the operating region of Goiener.

Table 8: Distribution of "Business initiatives with focus on Energy" according to the geographic scope of the actions

Geographic Scope	Number
Europe	3
Global	3
UK	2
USA	1
Belgium	1
Bilbao (Spain)	7
Wallonia (Belgium)	1

When it comes to the main targeted area of the initiatives a total of 5 different areas were identified with "Energy Efficiency" being the most relevant one, with 9 cases (50% of the total number of initiatives identified).

Table 9: Distribution of "Business initiatives with focus on Energy" according to the main targeted area

Main targeted area	Number
Demand management	3
Energy Efficiency	9
Renewable energy	1
Energy efficient behaviour	4
Achieve 100% renewable electricity	1

2.3.4. Business Initiatives with focus on Transport

Finally the last category of actions contains business initiatives with a focus on Transport. Similar to the Business Initiatives with focus on Energy, the drive behind these initiatives is a business model of a company.

Only 3 business initiatives were identified, all of which were cooperative instruments and all of which were located in Spain.

2.4. Non-policy driven interventions

Another type of intervention are those not actively and purposely driven by policy makers or companies but rather interventions that "just happen". In the WHY-Project those are referred to as non-policy driven or **natural interventions**. Natural interventions can best be described as fundamental change in our daily lives that the consumers have no say in or no possibility to influence. While there are multiple natural interventions possible, the WHY-Project will focus on two main ones, given by the WHY use cases.

1. **Global Pandemic:**
   As seen in the currently (as of May 2021) ongoing covid19 pandemic, everyday life was heavily affected. With regard to energy consumption, the most relevant effects of the pandemic was the strong shift towards people staying at home more and working from home where possible. This caused a change in the consumption behaviour of residential consumers.
2. **Black-Out:**
   Given the situation that a black-out occurs (for whatever reason) and that some parts of the electricity grid are capable of working in islanding mode, residential consumption behaviour will (at least temporarily) have to change in order to uphold grid operation. Consumption will have to be limited to the most relevant devices.
3. **Extreme weather situations:**
   Extreme weather situations like floods, heavy snowfall, etc. can disrupt our everyday life. People might stay at home instead of going into work or change their behaviour in other ways. As suchs these events (given that the energy supply is still working) will have an effect on the consumption behaviour of residential consumers.

As can be seen from the examples, these do not really fit inthe categories described above, as they are not triggered on purpose. Nevertheless these types of interventions need to be considered in the WHY-Project. The list will very likely be adapted during the WHY Use Case discussions described in Deliverable D 1.3.

2.5. Summary

The purpose of the task of identifying and clustering Policy Actions and Business Initiatives was to get an idea of what type of actions and initiatives are applied and how the ideas behind the policy instruments are translated into real life applications. This information is crucial for the definition of the interventions which will be applied to the Causal Model. The decision on which interventions will be considered in the later course of the WHY-project will be presented in Deliverable D1.3.

For the purpose of providing a basis to make this decision, a total of **131 different actions and initiatives** were researched by the WHY-consortium and described according to the parameters of the taxonomy developed, which can be found on the Zenodo-Page of the

WHY-project[3]. Of the 131 different actions and initiatives, 71 actions were categorized as "*Policy Actions with focus on energy*", 29 actions were categorized as "*Policy Actions with focus on transport*", 18 initiatives were categorized as "*Business Initiatives with Focus on Energy*" and finally 3 initiatives were categorized as "*Business Initiatives with Focus on Transport*". Additionally two non policy driven or natural interventions were discussed as a representation of intervention that are caused unintended.

4. Methodology for the identification of the modelling approaches in the field of energy system modelling

Apart from the interventions needed for the Causal Model, the WHY-Toolkit will consist of (mathematical) models representing certain areas of the household energy system. These aspects or parts need to be represented in the WHY-Toolkit to analyse the effects that decisions of inhabitants of residential buildings will have on the use of devices as well as the investment in new devices or investments in changes (e.g. renovation or insulation) of the buildings, etc. and thus the resulting energy consumption.

The stakeholders of the WHY-Toolkit have mentioned several requirements[4] that present a certain trade-off between fast computation time of the WHY-Toolkit versus degree of detail of the models and results. As can be expected a more detailed modelling approach for these areas of the household energy system would lead to a higher computation time. As such it was required to analyse and research existing approaches for (mathematical) models in order to choose the best fitting models to do the job. In this chapter of the Deliverable D1.2 the results of the research are presented. The decision on what models to implement in the WHY-Toolkit will be presented in Deliverable D1.3 as a result of the WHY Use Case Stakeholder involvement.

To make research results of the different areas of the household energy system comparable a standardised approach was applied, which will be described below.

1. **Definition of fields relevant to energy system models**
   As a first step, the different areas of relevance for the household energy system are defined taking into consideration the objectives of the project and the aspects required by the stakeholders to be included. The following areas, for which (mathematical) models need to be developed during the project were identified:
    a. Causal Models
    b. Models for different scales of energy systems
    c. Models for household appliances
    d. Models for electric mobility
    e. Models for energy efficiency approaches
    f. Models for energy sufficiency actions
    g. Models for energy management systems
    h. Models for energy storages
    i. Models for HVAC systems
    j. Models for energy generation technologies
    k. Business models for household electricity consumption

[3] https://zenodo.org/communities/why/?page=1&size=20
[4] Please refer to Deliverable D1.1 for further details.

2. **Research of simulation models**
   For the purpose of research, the different open and closed source models were researched, ranging from business solutions to research approaches. The goal of this research was, similar to the research done for the Policy Instruments and Business Initiatives, to create a better understanding of the types of models that can be used in each of the areas mentioned above.
   Aside from the purpose of creating a better understanding, the research also aimed at providing the foundation for the decision on which models to implement in the WHY-Toolkit, thus the research results need to identify the costs related to the models as well as the technical parameters (such as programming environment, required parameters, adaptability, etc.).
3. **Identification of the models applied in WHY**
   Following the research work, the decision on which models to use in the WHY Toolkit needs to be made. This is strongly dependent on the requirements of the WHY Use Cases, thus the decision will be described in Deliverable D1.3.

4.1. Causal Models

By definition (Guo et al., 2020), machine learning tasks are either predictive or descriptive. Beyond this, the way to understand causality on these models is by thinking of a scenario where some variables could be modified and the data-generating process is rerun. Nevertheless, causality usually is considered as these two (related) questions:

1) How much would some specific variables (features or labels) change if we manipulate the value of another specific variable? or
2) By modifying the value of which variables could we change the value of another variable?

These questions are referred to as causal inference and causal discovery questions, respectively. For learning causal effects, we figure out to what extent manipulating the value of a potential cause (intervention) would influence a possible effect (on the system outcome).

A Causal Model is a mathematical abstraction that quantitatively describes the causal relations between the variables. First, causal assumptions or prior causal knowledge can be represented by an incomplete Causal Model (Pearl, 2019). Then, what is missing can be learned from data.

The two most well known causal models are the Structural Causal Models (SCMs) and the Potential Outcome Framework (POF). They are considered as the foundations because they enable a consistent representation of prior causal knowledge, assumptions, and estimates. In particular, the POF takes as a starting point the potential outcomes (some model) and relates these via the observation rule to observed outcomes. In contrast, the SCM perspective defines a model based on the observed outcomes from which the potential outcomes can then be derived. Let us consider a linear model from both perspectives.

The two formal frameworks are logically equivalent, which means an assumption in one can always be translated to its counterpart in the other. There are also some differences between them. In the POF, the causal effects of the variables other than the treatment and the special variables such as instrumental variables are not defined. This is a strength of this framework as we can model the interesting causal effects without knowing the complete causal graph. While in SCMs, we are able to study the causal effect of any variable. Therefore, SCMs are often preferred when learning causal relations among a set of variables. Conversely, if the goal is narrowly to estimate a given treatment effect, developing estimators can be more straightforward using the potential outcomes framework. Given that this is the primary goal of WHY, SCMs are going to be used in the project.

An SCM often consists of two components: the causal graph (causal diagram) and the structural equations.

- **Causal Graphs**: A causal graph forms a special class of Bayesian network with edges representing the causal effect, thus it inherits the well defined conditional independence criteria. The expert knowledge from WHY will be represented through Directed Acyclic Graphs (DAG). A DAG $G = (V, E)$ is composed of a set of variables$V$(vertices in the graph language) and a set of directed edges E between variables. In a causal graph, each node represents a random variable including the treatment, the outcome and other observed and unobserved variables (pi: predict/infer, 2019)
- A directed edge $x \to y$ denotes a causal effect of x on y. A path is a sequence of directed edges and a directed path is a path whose edges point to the same direction. In this work, as is common in the field, we only consider directed acyclic graphs where no directed path starts and terminates at the same node. Given a SCM, the conditional independence embedded in its causal graph provides sufficient information to confirm whether it satisfies the criteria such that we can apply certain causal inference methods.
- **Structural Equations**: Each directed edge in the causal graph will map to a function $f(x) = y + \epsilon$ whereϵ denotes the error term. This function f could take an arbitrary number of parameters that will need to be fitted to data. The Structural Equations is the set of these functions already fitted to the data.

4.1.1. The seven tasks provided by causal models

According to (Pearl, 2019), causal models need to provide 7 tasks to be useful. In order to classify the libraries to build these models, we follow this classification and also include a couple of implementation aspects we should consider. The list of tasks and aspects considered is provided below:

- **Tasks**:
  - **Encoding Causal Assumptions – Transparency and Testability**: Transparency enables analysts to discern whether the assumptions encoded are plausible or whether additional assumptions are warranted. Testability permits to determine whether the assumptions encoded are compatible with the available data and, if not, identify those that need repair. Testability is facilitated through a graphical criterion called d-separation,

which provides the fundamental connection between causes and probabilities (Pearl, 2019).
  - **Do-calculus and the control of confounding**: For models where the "back-door" (graphical criterion to manage confounding) criterion does not hold, a symbolic engine is available, called do-calculus, which predicts the effect of policy interventions whenever feasible (Shpister and Pearl, 2008).
  - **The Algorithmization of Counterfactuals**: This task formalizes counterfactual reasoning within the graphical representation. Every structural equation model determines the truth value of every counterfactual sentence.
  - **Mediation Analysis and the Assessment of Direct and Indirect Effects**: This task concerns the mechanisms that transmit changes from a cause to its effects which is essential for generating explanations and counterfactual analysis must be invoked to facilitate this identification.
  - **Adaptability, External Validity and Sample Selection Bias**: Robustness is recognized by AI researchers as a lack of adaptability that comes out when environmental conditions change. The do-calculus offers a complete methodology for overcoming bias due to environmental changes. It can be used both for re-adjusting learned policies to circumvent environmental changes and for controlling disparities between non-representative samples and a target population (Bareinboim and Pearl, 2016).
  - **Recovering from Missing Data**: Using causal models of the missingness process can formalize the conditions under which causal and probabilistic relationships can be recovered from incomplete data and, whenever the conditions are satisfied, produce a consistent estimate of the desired relationship.
  - **Causal Discovery**: The d-separation criterion detects and enumerates the testable implications of a given causal model. This opens the possibility of inferring, with mild assumptions, the set of models that are compatible with the data, and to represent this set compactly; in certain circumstances, the set of compatible models can prune significantly to the point where causal queries can be estimated directly from that set(Jaber et al., 2018).
- **Implementation aspects:**
  - **Licence**: The licence that the library and the rest of the environment (IDE) have. Only open source models have been found.
  - **Programming Language**: The programming language used to build the models. All models studied use either R or Python (and some of them can accept both).
  - **Documentation and support channels**: In all cases there is good written documentation (How to tutorials, API descriptions and Q&A guides) and a living community.
  - **Support tools to write Causal Diagrams**: Has the library supporting tools to graphically "write from scratch", "load and modify" an "convert from different file formats" Causal Diagram?

4.1.2. Relevant Libraries

Several libraries implementing the previous aspects have been found: DAGitty[5], DoWhy[6], CausalGraphicalModels[7], Casuality[8] and CausalInference[9].

Table 10: Main characteristics of the different libraries to build causal models

	Packages				
Aspects	**DAGitty**	**DoWhy**	**CausalGraphicalModels**	**Casuality**	**CausalInference**
Encoding Causal Assumptions – Transparency and Testability	X	X	X	X	X
Do-calculus and the control of confounding	X	X	X	X	X
The Algorithmization of Counterfactuals	X	X		X	X
Mediation Analysis and the Assessment of Direct and Indirect Effects	X	X	X	X	X
Adaptability, External Validity and Sample Selection Bias	X	X			
Recovering from Missing Data		X			
Causal Discovery	X	X	X	X	
Support tools to write Causal Diagrams	X	X	X	X	X
Licence	GNU	MIT	MIT	Open	BSD
Programming Language	R	R/Python	Python	Python	Python
Documentation and support channels	X	X	X		X

DoWhy is the only library that covers all of the tasks. Moreover, has a very permissive licence, has several bindings to different programming languages and has one of the most active communities so it is the most promising tool to be selected.

4.1.3. Causal Models to be developed

During the WHY project, several Causal Models will be developed. In particular, groups of experts will discuss and construct a causal model for investment decisions (including “investment” decision on energy efficiency and sufficiency actions) on each of the following aspects of the energy transition:

[5] http://www.dagitty.net/
[6] https://github.com/Microsoft/dowhy
[7] https://github.com/ijmbarr/causalgraphicalmodels
[8] https://github.com/akelleh/causality
[9] https://causalinferenceinpython.org/

- **Buildings**: this group will cover the HVAC system and building thermal insulation including sufficiency aspects like the thermostat temperature.
- **Appliances**: this group will include the use and renovation of all appliances in a house.
- **Flexibilities**: this group will assess the installation of distributed generation, energy storage and the participation on the different flexibility markets that exist. Moreover, the control strategy to operate these components will also be included in the discussion.
- **Transportation**: this group will discuss the need to travel, the transport mode owned and finally, the one used.

These groups will build the first SCM using DAGs and thus represent the causal relationships and effect between the identified variables and also the assumptions about them, in the same way the DAGs allow identifying the variables that we can use to carry out interventions. For more information about the methodology used to build these models, the reader is referred to Deliverable D2.2.

Finally, the structural equations will be derived from the data sets retrieved in the project. In particular, a variety of consumption profiles based on the behaviour of inhabitants of residential buildings. More information about the datasets used in the WHY project is given in Deliverables D2.1 and D2.3.

4.2. Models for different scales of energy systems

The models considered in this chapter try to provide a holistic overview of the energy consumption of different scales of energy systems. Depending on the chosen scale, these energy systems can be single buildings up to complex larger scale energy supply systems. It is often the case that small scale system models tend to be by far more detailed than large scale system models due to limits in computation time, etc. As a result, these models generate data on energy consumption, operational costs or CO_2 emissions amongst others.

From a modeling perspective, models for energy systems are a collection of different models working together in a common, unified framework. Depending on the scale of the model, these different models are as detailed as valves and pipes within a building or simplified representation of entire building blocks. The quality and detail of results is strongly dependent on the scale of the model and the computation time available.

The next paragraphs will provide a brief overview of models found during the research, the list is by no means exhaustive, but should provide the reader with a better understanding of possibilities and scales of models for energy systems. A total of 10 different models were researched.

- **Load Profile Generator [Building Scale]:**
  Complex and powerful modeling tool for residential energy consumption focusing on individual households. It performs a full behaviour simulation of the people in a household and uses that to generate load curves (Pflugradt, 2016).

- **Energy Plus [Building Scale]:**
  EnergyPlus (U.S. Department of Energy, 2020) is an energy analysis and thermal load simulation program. Based on a user's description of a building's geometry, construction materials, usage and systems, EnergyPlus calculates the heating and cooling loads necessary to maintain thermal control setpoints, conditions throughout secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building would.
- **EnergyPLAN [Large Scale Energy Systems]:**
  The EnergyPLAN model (Lund and Zinck Thellusfen, 2020) is a computer model for Energy Systems Analysis. The analysis is carried out in hourly steps for one year. And the consequences are analysed on the basis of different technical simulation strategies as well as market-economic simulation strategies. The main purpose of the model is to assist the design of national energy planning strategies on the basis of technical and economic analyses of the consequences of different national energy systems and investments. However, the model has also been applied to the European level as well as to a local level such as towns and/or municipalities.
- **MATLAB & Simulink [General Modelling Environment]:**
  MATLAB® and Simulink®[10] provide an integrated platform with both data analytics and Model-Based Design. One can build predictive models of energy demand and optimization models to minimize cost in MATLAB. Then, combine these with a system model built with Simulink and Simscape™ that integrates power electronics and controls. Deployment can be to embedded systems, or to enterprise or cloud environments.
- **Simscape Electrical Specialized Power Systems [Different Scales of Energy Systems]:**
  Simscape Electrical Specialized Power Systems software[11] is a modern design tool that simulates power systems rapidly and easily. It uses the Simulink environment, allowing you to build a model using simple click and drag procedures. Not only can you draw the circuit topology rapidly, but your analysis of the circuit can include its interactions with mechanical, thermal, control, and other disciplines.
  Simscape Electrical Specialized Power Systems software belongs to the Physical Modeling product family and uses MATLAB toolboxes and Simulink blocksets.
  This software and other products of the Physical Modeling product family work together with Simulink software to model electrical, mechanical, and control systems.
- **TRaNsient SYstem Simulation program [Different Scales of Energy Systems]:**
  TRNSYS[12] is an extremely flexible graphically based software environment used to simulate the behaviour of transient systems.
  TRNSYS is made up of two parts. The first is an engine (called the kernel) that reads and processes the input file, iteratively solves the system, determines convergence, and plots system variables. The kernel also provides utilities that (among other things) determine thermophysical properties, invert matrices, perform linear regressions, and interpolate external data files. The second part of TRNSYS is an extensive library of components, each of which models the performance of one part of the system. The standard library includes approximately 150 models

[10] https://de.mathworks.com/videos/optimization-in-energy-management-systems-1561902499222.html?s_tid=srchtitle
[11] https://de.mathworks.com/products/simscape-electrical.html
[12] http://www.trnsys.com/index.html

ranging from pumps to multizone buildings, wind turbines to electrolyzers, weather data processors to economics routines, and basic HVAC equipment to cutting edge emerging technologies. Models are constructed in such a way that users can modify existing components or write their own, extending the capabilities of the environment.

- **RC-Building Simulator [Building Scale]:**
  A physics-based model to simulate the thermal behaviour of the building using a resistor-capacitor (RC) model (Jayathissa, 2017). This is based on an electrical analogy corresponding to the equivalent thermal physics. The model consists of one internal thermal capacitance, and five thermal resistances. This is also known as a 5R1C model and is based on the ISO 13790 standard.
- **ESP-r [Building Scale]:**
  A building energy simulation program for integrated modelling of energy performance. It is mostly used by researchers for detailed studies. Heat, air, moisture, light and electrical power flows can be simulated. ESP-r has a number of developers world-wide and its distribution is managed under GitHub source code control
- **IDA ICE [Building Scale]:**
  IDA Indoor Climate and Energy (ICE)[13] is a program for study of the indoor climate of individual zones within a building, as well as energy consumption for the entire building.
- **Modelica Building Systems [Different Scales of Energy Systems]:**
  The Modelica open-source BuildingSystems library[14] is developed for dynamic simulation of the energetic behaviour of single rooms, buildings and whole districts. The simulation models of the library describe the dynamic energy balance of the building envelope inclusive of its boundary conditions (ambient climate, user behaviour). The corresponding energy plant system - e.g. a solar heating system - can be included optionally in an entire "Building System" model.

4.3. Modelling appliances

While models for different scales of energy systems try to provide a holistic point of view on complex energy systems, models for appliances provide a detailed mathematical representation of a single (electric) appliance in the household. The models are often embedded in the framework of the energy system models. In the case of the WHY project appliances are described as devices which run a fixed program and cannot be disrupted by an external control. As a result, these mathematical representations are distinct load profiles considered for each device. The load profiles considered in the WHY-project are taken from actual measurements of devices as described in (Pflugradt, 2016) and our own set of measurements (see Deliverable D2.3 for details). Since only loads which are not going to be subject to interruption are considered, these appliances are represented by fixed load profiles. The load profiles have the duration of the operational time of the device and do not represent a full days' worth of values. If load shifting is an option (due to an energy management system), the starting time of the devices can be changed within preferred operational times. It needs to be stated though, that the real flexibility potential lies within the devices mentioned in the systems described later in the deliverable.

[13] https://www.equa.se/en/ida-ice
[14] https://modelica-buildingsystems.de/

4.4. Modelling mobility

Multi-agent systems have been an active area of research in the last 3 decades for transportation modelling. The literature shows a great amount of research concerning traffic simulation through agent-based systems. The most important projects in this area are detailed as follows.

- **Sumo** (Krajzewicz et al., 2012): An open-source, microscopic and multi-modal traffic simulation package designed to handle large road networks and establish a common test-bed for algorithms and models from traffic research. It facilitates interoperability with external applications during run time, using Traffic Control Interface. SUMO comes with a mechanism to import cartographic material and automatically generate an input for traffic simulation taking data directly from OpenStreetMap. The main drawback of SUMO is having to explicitly define by hand multi-modal route steps for each citizen instead of the simulation being able to calculate them according to the existing available public transport vehicles.
- **MATSim** (Axhausen, Horni, et al., 2016): An open-source, agent-based transportation simulation that is able to simulate large-scale scenarios. Currently, MATSim offers a framework for demand-modelling, agent-based mobility-simulation (traffic flow simulation), re-planning, a controller to iteratively run simulations as well as methods to analyse the output generated by the modules. Originally MatSim only considered simulations for private car traffic, trimming its capabilities to answer sophisticated questions posed to advanced models that include several types of vehicles. However, in later versions the functionality was extended to all kinds of public transports, including pedestrians and cyclists.
- **Vissim** (Fellendorf, 1994): A microscopic, time step and behaviour based simulation model developed to analyse the full range of functionally classified roadways and public transportation operations. It models cars with a high-fidelity model based on the Wiedemann-Model. and allows to very accurately create traffic simulations defining the amount of vehicles and types that travel through its network. It is very recommended for highly realistic studies but not suitable for large scale simulation studies.
- **PRIMES-TREMOVE** (Sikos and Capros, 2014): An economic model for transportation simulation that combines modelling of micro-economic behaviour concerning distribution of mobility and vehicle choices with detailed representation of transport technologies. It contains a transport demand module based on decision trees emulating the decision process of different consumer profiles choosing their best transport method according to their income constraints and behaviour characteristics.

These methodologies are relatively easy to follow and have many proven success stories but have a fundamental problem: they focus primarily on the calculation and estimation of routes and congestion avoidance, but fail to consider the social behaviour which influences the decision of using one transport method or the other. Simulations need to consider this previous step to include how the social behaviour affects the output of the evaluation of a scenario. This implies modelling social preferences when travelling such as time cost, comfort, monetary cost or environment friendly awareness. Actual platforms for road simulation do not cover these needs, either due to the impossibility to parameterise the initial system configuration according to social variables, or due to the distribution of such modules as additional commercial packages. Given that this is the primary objective of this task, any of these simulation platforms is adequate for the task.

In order to overcome this problem, we plan to follow a similar strategy to what we have considered for appliances (see Section 3.3). Nevertheless, this case is not as simple as that of the appliances. The energy consumption of a trip primarily depends on the transport mode and the distance traveled. Two different approaches are going to be used to model these aspects.

For modelling the vehicle energy consumption (and its environmental emissions), the Handbook of Emission Factors for Road Transport (HBEFA) (Notter et al., 2019) database will be used. The HBEFA was originally conceived at the request of the German, Swiss and Austrian environmental protection agencies. Currently, other countries (Sweden, Norway and France), in addition to the Joint Research Center (JRC) of the European Commission, support HBEFA. The HBEFA provides information about the energy consumption and emission factors, that is, the specific emission in g/km corresponding to all current vehicle categories (passenger cars, light commercial vehicles, heavy goods vehicles, buses and motorcycles), each of them divided into different categories and for a wide variety of traffic situations. Energy consumption for the different fuels (diesel, gasoline, hybrid, electricity, hydrogen, CNG, etc) are provided as well as emission factors for all major regulated and unregulated pollutants. The first version (HBEFA 1.1) was released in December 1995 and has since undergone several updates and enhancements. The current version (HBEFA 4.1) dates from August 2019.

Table 11 shows the taxonomy of means of transport that will be used in this project. In addition to this classification, it indicates the type (or types) of energy that each vehicle uses and the equivalent model of HBEFA that will be used. The table is also matching each particular vehicle and its corresponding HBEFA model.

On the other hand, to measure the distance travelled we will use the methodology from (Plötz et al., 2017) also used in (Reul et al., 2021). In this research activity, the authors fit different Weibull distributions to a database of daily travel from different countries and then use the fitted distribution to assess the project at hand (like the suitability of Plug-in hybrid vehicles or autonomous drivers). In our case, we will use it to simulate the travel distances of each journey. If possible, we will fit our own distribution to the data currently available in the different National Statistical Institutes.

Table 11: Transport means taxonomy

<table>
<tr><th colspan="5" rowspan="2">Clasificación</th><th colspan="4">Type of energy used and equivalent model of HBEFA</th></tr>
<tr><th>Animal traction</th><th>Electric</th><th>Hybrids</th><th>Combustion</th></tr>
<tr><td rowspan="8">Individual</td><td rowspan="4">Public</td><td colspan="3">Saddle / Animal-drawn vehicles</td><td>Ø</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td colspan="3">Bicycles / Scooters / Segways / etc.</td><td>Ø</td><td>eBike</td><td>--</td><td>--</td></tr>
<tr><td colspan="3">Mopeds (<50 km/h) / cars without a license</td><td>--</td><td>eScooter</td><td>--</td><td>Moped <=50cc Euro-5</td></tr>
<tr><td colspan="3">Motorcycles (> 50 km / h)</td><td>--</td><td>MC BEV</td><td>--</td><td>MC 4S <=250cc Euro-6</td></tr>
<tr><td rowspan="4">Private</td><td colspan="3">On foot / Saddle / Animal drawn vehicles</td><td>Ø</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td colspan="3">Bicycles / Scooters / Mobility Vehicles</td><td>Ø</td><td>eBike</td><td>--</td><td>--</td></tr>
<tr><td colspan="3">Mopeds</td><td>--</td><td>eScooter</td><td>--</td><td>Moped <=50cc Euro-5</td></tr>
<tr><td colspan="3">Motorcycles</td><td>--</td><td>MC BEV</td><td>--</td><td>MC 4S <=250cc Euro-6</td></tr>
<tr><td rowspan="17">Collective</td><td rowspan="6">Public</td><td rowspan="4">Fixed route</td><td rowspan="2">Predictable</td><td>Metro / Tram / Train</td><td>--</td><td>Train</td><td>--</td><td>--</td></tr>
<tr><td>Funicular / Elevator</td><td>--</td><td>Elevator</td><td>--</td><td>--</td></tr>
<tr><td rowspan="2">Unpredictable</td><td>City bus</td><td>--</td><td>UBus Electric Std >15-18t</td><td>UBus Std >15-18t HEV Euro-VI</td><td>UBus Std >15-18t Euro-VI</td></tr>
<tr><td>Coach</td><td>--</td><td>Coach BEV Std <=18t</td><td>--</td><td>Coach Std <=18t Euro-VI</td></tr>
<tr><td rowspan="2">Variable route</td><td colspan="2">Taxis</td><td rowspan="2">--</td><td rowspan="2">PC BEV</td><td rowspan="2">PC PHEV diesel Euro-6ab (EI)</td><td rowspan="2">PC diesel Euro-6ab
PC petrol Euro-6ab</td></tr>
<tr><td colspan="2">Rental cars</td></tr>
<tr><td rowspan="11">Private</td><td rowspan="10">Passenger cars</td><td colspan="2">Micro cars</td><td rowspan="10">--</td><td rowspan="10">PC BEV</td><td rowspan="10">PC PHEV diesel Euro-6ab (EI))</td><td rowspan="10">PC diesel Euro-6ab
PC petrol Euro-6ab</td></tr>
<tr><td colspan="2">A segment (mini cars)</td></tr>
<tr><td colspan="2">B segment (small cars)</td></tr>
<tr><td colspan="2">C segment (medium cars)</td></tr>
<tr><td colspan="2">D segment (family cars)</td></tr>
<tr><td colspan="2">E segment (executive)</td></tr>
<tr><td colspan="2">F segment (luxury)</td></tr>
<tr><td colspan="2">S segment (sport)</td></tr>
<tr><td colspan="2">M segment (monovolumen)</td></tr>
<tr><td colspan="2">J segment (SUV)</td></tr>
<tr><td colspan="3">Light commercial vehicles</td><td>--</td><td>LCV BEV N1-II</td><td>LCV PHEV petrol N1-II Euro-6</td><td>LCV diesel N1-II Euro-6c</td></tr>
</table>

4.5. Modelling energy efficiency approaches

This chapter sets the focus on measures to increase the energy efficiency in buildings and how these measures affect the simulation models. While these approaches are not represented in actual models themselves, they heavily influence the parameters of existing models for appliances or buildings. Thus the WHY-consortium analysed the relevance of the approaches and how they can be considered.

Energy Efficiency approaches are categorised in three main categories with corresponding subcategories. The measures presented in this chapter highlight the most relevant measures for the household-sector. These categories are:

- Renovation measures
- Energy Labels and Certificates of Devices
- Energy efficiency measures

The next paragraphs provide a description of the categories.

Renovation measures:

- **Windows**:
  - **Installation of Low emissivity glass:**
    According to (Culp et al., 2015) low-e storm windows are multilayer nanoscale coatings of materials that reflect light in the mid-infrared spectrum (thermic radiation) but are still transparent to visible light. As a result, low-e storm window coatings reduce radiative heat loss from the warmer interior to the colder exterior and also lower solar heat gain through the glazing. The primary purpose of a low-e storm window is to reduce the U-values of buildings[15]. These low-e coatings are called solar selective or solar control low-e coatings.
  - **Installing window-shading**
    Window shades come in a variety of types but all share the same purpose: to add privacy, regulate lighting in rooms. Regarding energy efficiency their main purpose is to reduce solar gains through windows and depending on the type of shade also reduce heat loss during the heating season. Shades can be installed either on inside or outside a window, which strongly affects the energy efficiency effects.
  - **Replacement of windows with multi-glazed windows**:
    Complete exchange of windows and frames with new frames and windows with multiple glazes. Commonly two or three layers are applied. Between the individual window-panes (noble) gasses such as Argon, Xenon or Krypton are used as additional insulation. In older examples air or SF6 was used, both are outdated and not standard anymore, with the use of SF6 being prohibited. Another important factor for energy efficiency is the material of the frame and the seal used.
- **Insulation**:

[15] https://ec.europa.eu/energy/content/u-value-building-element_en

- **External Thermal Insulation**:
  The general approach for improving the energy efficiency of the building is improving the external insulation. For that purpose an insulation is applied to the outside walls of the building. A better insulation can be reached through multiple different approaches, for instance by installing thermal insulation compound systems (a combination of different thermal insulation types), installing a curtain wall (often a wooden wall in front to the core wall of the building with insulation in between) or implementing a core insulation (insulation is directly injected into the wall of a building).
  The insulation material depends on the type of method applied, but there is a vast variety from natural materials (cork, sheep wool, etc.) to artificial materials (XPS, styrofoam, etc.) that is being applied. Also the structure of the material can show a large variety ranging from solid plates over mats to loose materials.
- **Internal Thermal Insulation**:
  An easier to apply, albeit less efficient method of improving the energy efficiency of a building is the application of internal insulation, which is applied to the inside walls of buildings, the floors or the inside of the roof. Depending on the area to which the insulation is applied, different methods and material can be used. For attics for instance it makes a difference whether or not it should be accessible, in which chase insulation panels (on which you can walk) or the installation of a raised floor and using pour-in insulation is an option. For inside walls it is important to differentiate between cavity walls, in which case pour-in insulation or insulation mats can be used or if there are solid walls, in which case insulation panels or insulation mats need to be used.
- **Floor insulation**:
  Floor sealing is of importance when rooms are above a cellar or on the bottom floor in houses without a cellar. Furthermore they play an important role when floor heating is applied. The type of insulation and insulation material strongly depends on the specifics of the building and the floor and whether there is a floor heating installed or not. Regardless of these specifics the insulation material must be durable due to the constant strain it has to endure.
- **Roof Sealing**:
  Thermal losses and gains of the roof area amount for a very large proportion of the total losses or gains due to its size and exposure. As such thermal insulation of the roof plays an important role when trying to improve the overall efficiency of a building. Insulation options are below rafter, in between rafter and on rafter insulation for pitched roofs and internal or external insulation for flat roofs. There are multiple different materials with different properties available today.
- **Roof Sarking**:
  Roof Sarking is the process of installing a thin insulating membrane directly underneath the roof. It works as a sort of “reflective” insulation with the purpose of reflecting radiant heat and thus preventing it from entering the building from outside (summer time) or leaving the building from the inside (winter time).

- **Air-Sealing**:
  Sealing houses against air leakage is one of the simplest upgrades one can undertake to increase comfort in a house. Air leakage accounts for 15–25% of winter heat loss in buildings (Reardon, 2013) and can contribute to a significant loss of coolness in climates where air conditioners are used. In general, air leakage is a problem which needs a detailed analysis varying from house to house. The first step, even before sealing, is to detect leaks. This can be done personally by inspecting doors, windows, edges, spots, where different materials meet each other, vents, skylights and exhaust fans. A more professional approach is to use a blower door, which reduces the pressure in the house. In the following, air from outside will enter the house because of the pressure difference. The air leakage rate can be measured this way, and by using smoke, the actual leaks can be detected.
- **Insulation of pipes**:
  Heat losses in the pipes of the heating system account for a large (up to 50% (Pink et al., 2020)) of the total heat losses in central European buildings. This is due to the fact that the pipes have to be kept at operating temperature and are constantly losing thermal energy. Insulation of pipes consists of installing shells or ducts made from a thermal insulator such as glass or rock wool (from basalt) in the pipes. In addition to mineral wool, other materials such as plastic foam or vapour barrier coatings can also be used.

Energy Labels and Certificates:

- **LEED**[16] (USA):
  LEED (Leadership in Energy and Environmental Design) is the most widely used green building rating system in the world. Available for virtually all building types,it provides a framework for healthy, highly efficient, and cost-saving green buildings. LEED certification is a globally recognized symbol of sustainability achievement and leadership .
- **BREEAM**[17] (UK):
  BREEAM is the world's leading sustainability assessment method for master planning projects, infrastructure and buildings. It is an international scheme that provides independent third party certification of the assessment of the sustainability performance of individual buildings, communities and infrastructure projects. It recognises and reflects the value in higher performing assets across the built environment lifecycle, from new construction to in-use and refurbishment.
- **Energy Star**[18] (US):
  Energy Star is a program run by the U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE) that promotes energy efficiency.The program provides information on the energy consumption of products and devices using different standardized methods. The Energy Star label is found on more than 75 different certified product categories, homes, commercial buildings, and industrial plants.

[16] https://www.usgbc.org/leed/why-leed
[17] https://www.breeam.com/discover/how-breeam-certification-works/
[18] https://www.energystar.gov/

- **Rescaled EU Labels**[19] (EU):
  As a result of the development of more and more energy efficient products, classes above A (A+, A++ and A+++) have appeared. The solution is therefore to rescale these labels to the original A to G scale. The class A will initially be empty to leave room for technological developments in the future. Every appliance that requires an energy label needs to be registered in EPREL (European Product Registry for Energy Labelling) before being placed on the European market by the supplier. A QR code is placed on the label for the client to have access to this public information. An important change in the new ecodesign rules is the inclusion of elements to further enhance the reparability and recyclability of appliances. Several of the new measures include requirements, such as ensuring the availability of spare parts and access to repair and maintenance information for professional repairers.
- **Energy Performance Certificates**[20] (EU):
  Similar to the EU Labels for Appliances the Energy Performance Certificates (EPC) are basically energy labels for buildings. They are important instruments that are expected to contribute to the energy performance of buildings. Following the Energy Performance of Buildings Directive (EPBD), an EPC shall include the energy performance of a building and the reference values, as well as the recommendations for the cost-optimal or cost-effective improvements of the energy performance of a building or building unit. Within the national context, it is up to the Member States to decide on the performance rating of the representation (i.e. energy level vs. continuous scale) as well as the type of recommendations (i.e. standardised vs. tailor-made).

Energy Efficiency measures in residential buildings need to be considered separately for renovation measures and energy labels for appliances. Energy Performance Certificates play a special role, while being an energy label the values of the Certificate are changed when renovation actions are made. The main factor for thermal losses of buildings is the U-value. (Lymath, 2015) describes the U-value as follows:

> *"Thermal transmittance, also known as U-value, is the rate of transfer of heat through a structure (which can be a single material or a composite), divided by the difference in temperature across that structure. The units of measurement are W/m²K. The better-insulated a structure is, the lower the U-value will be. Workmanship and installation standards can strongly affect thermal transmittance. If insulation is fitted poorly, with gaps and cold bridges, then the thermal transmittance can be considerably higher than desired. Thermal transmittance takes heat loss due to conduction, convection and radiation into account."*

Replacing Windows - rough estimation

In general, the effect of replacing windows strongly depends on the starting position. For buildings with windows with high U-values it is highly efficient to change windows, while buildings with modern windows with low U-values should not consider this option. In addition, the effect depends on the climate and weather conditions. In order to make an

[19] https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ energy-label-and-ecodesign
[20] https://ec.europa.eu/energy/eu-buildings-factsheets-topics-tree/energy-performance-certificates_en

estimation of the effects of changing windows the following rough calculation is quite useful:

$$J_{loss} = u \cdot A \cdot \Delta T \cdot t, \tag{1}$$

where J_{loss} is the heat loss of the building in kWh, u is the U-value in W/(m^2 K), A is the total area of the windows in m^2, ΔT is the temperature difference between inside and outside in K and t is the considered time in hours. Taking this formula, the heat losses and heat gains can be roughly estimated before and after the window change.

Example:
An old house in Austria has 30 m^2 of box windows (u-value = 2.2). The inside temperature of the house is always around 20°C. The heating relevant months are December, January and February with an average outside temperature of 0 °C. The heat loss only through the windows during the relevant heating period is:

$$J_{loss-old} = 2.2 \cdot 30 \cdot 20 \cdot 24 \cdot 90 \ = \ 3.8\, MWh \tag{2}$$

Modern triple-pane windows have a U-value of about 0.8. Hence,

$$J_{loss-new} = 0.8 \cdot 30 \cdot 20 \cdot 24 \cdot 90 \ = \ 1.0\, MWh. \tag{3}$$

In this situation replacing windows will save about 2.8 MWh of heat demanded each year. Economic and environmental effects highly depend on the heating system. In the case of electrical heating, where 1 kWh costs about 20 c€ right now in Austria, the economical savings due to the window change are in the range of 560 euros each year.

For the calculation the values shown in Table 12 have been considered:

Table 12: Representative u-Values for different window types (Röster, 2012)

Type	u-Value [W/m²K]
Insulating glass window	2.5 - 4
Coupled window	2.5 - 3.7
Box Window	2.2
Modern heat insulation window (2 panes)	1.1 - 1.5
Modern heat insulation window (3 panes)	0.7 - 0.9

Replacing Windows - exact calculation

In addition to the u-value, many other parameters affect the heat loss and gain through windows. For example, the alignment of the windows and their relative position to the sun, the amount of radiation penetrating through the windows, or the air leakage. In addition, using real climate data (temperature and solar radiation) will improve the exactness of the estimation. Detailed, dynamic simulations are supported by building simulation software like **TranSys, EnergyPlus or IdaICE.** When estimating the effect of changing windows, two simulations need to be done: one with the old windows, and one with the new ones.

Storm Windows - rough estimation

As with full window replacement the rise in energy efficiency due to storm windows strongly depends on the starting point. Storm windows are most effective when they are attached to older, inefficient, single-pane primary windows that are still in decent, operable condition. Adding an interior storm window to a new, dual-pane primary window will not improve performance much, and adding one to a decaying, old primary window will not extend the primary window's lifespan even though it will give the efficiency rating a boost.

Exemplarily the change in the parameters due to the addition of different types of storm windows to a Wood Double Hung, Single Glazed window is shown below. The study of (Culp et al., 2015) provides the values shown in Table 13 for different types of windows and frames.

Table 13: Example of Representative values for different Storm Window Types (Culp et al., 2015)

Base Window	Storm Type	u-Value [W/m²K]	SHGC	VT
Wood-Double Hung, single glazed	none	5	0.61	0.66
	Clear Exterior	2.7	0.54	0.57
	Clear Interior	2.6	0.54	0.59
	Low-E, Exterior	2	0.46	0.52
	Low-E, Interior	1.9	0.5	0.54

Improving Insulation - rough estimation

Similar to the effects of changing windows, the effect of adding insulation to a house strongly depends on the starting situation. Adding insulation to a house with old solid bricks in a cold climate will affect the energy efficiency enormously, whereas adding insulation to a passive house will bring very limited efficiency benefits l. Insulation protects from heat losses on cold days and from heat gains on hot days. Again, an analysis has to be made twice: once of the starting situation (house in the current state) and once of the improved situation (house with insulation). In order to make an estimation of the effects the insulation may have, the following formula is quite useful:

$$R_{insulated} = \frac{1}{u_{insulated}} = 1/u_{not\ insulated} + th/\lambda \qquad (4)$$

The u-value is the parameter accounting for the heat loss of a building in W/(m^2 K). λ describes the thermal conductivity of the insulation in W/(m·K) and th stands for the thickness of the insulation in m. The u-value then can be used to make an estimation of the heat loss through the walls, the roof and the floor using the formula given for J_{loss}.

Example:
The following situation is considered exemplarily: An old house in Austria has 100 m^2 of old brick walls (u-value = 1.5 $W/(m^2 \cdot K)$). An insulation of 0.1 m PIR panels (= 0.023) is added to the envelope of the house leading to a u-value of:

$$u_{insulated} = \frac{1.5 \cdot \frac{0.024}{0.1}}{1.5 + \frac{0.023}{0.1}} = 0.2\ \frac{W}{m^2 K} \tag{5}$$

The inside temperature of the house is always around 20°C. The heating relevant months are December, January and February with an average outside temperature of 0 °C. The heat loss through the walls during the relevant heating period is:

$$J_{loss,\ not\ insulated} = 1.5 \cdot 10 \cdot 20 \cdot 24 \cdot 90 = 6.5\ MWh \tag{6}$$

$$J_{loss,\ insulated} = 0.2 \cdot 100 \cdot 20 \cdot 24 \cdot 90 = 0.9\ MWh \tag{7}$$

In this situation, insulation will save about 5.6 MWh of heat demanded each year. Economic and environmental effects depend on the heating system. In the case of electrical heating, where 1 kWh costs about 20 cents right now in Austria, the economical savings due to the isolation are in the range of 1 120 euros each year.

The rough estimation is extremely helpful to decide if investments will pay back (and when) or not. This decision can only be made when climate and the actual state of the building are roughly known. Economic and environmental effects additionally depend on the heating system.

Table 14 shows a representation of different u-values for wall materials.

Table 14: Example of Representative values for different wall types and thicknesses (Eicke-Hennig, 2017), (U-wert.net GmbH, 2021)

Type	U-Value [W/m²K]	Wall thickness [cm]
Old solid brick wall	**1.5**	**38**
Old horizontal coring brick wall	**1.44**	**25**
Old vertical coring brick wall	**1.39 - 1.5**	**30**
Modern thermo bricks without adding insulation	**0.24**	**40**
	0.315	**30**
	0.375	**25**
Wall plus insulation	**0.14 - 0.2**	**29**
Wood frame construction	**0.27**	**40**
Cellular concrete without insulation	**0.19**	**40**
	0.26	**30**
	0.3	**25**

It needs to be stated at this point, that the u-value is a simplification. The thermal conductivity of bricks and concrete can vary within a larger field as shown in Figure 1 and the combination with insulation materials are manifold.

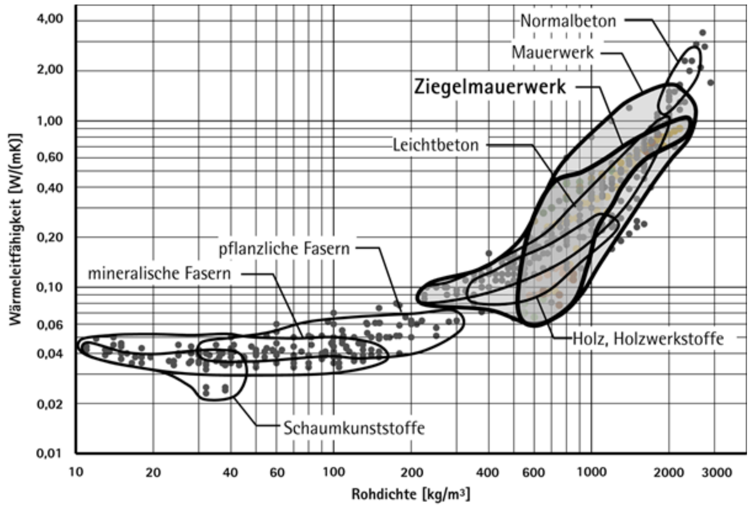

Figure 1: U-values in dependence of material and density (Pech et al., 2018)

Additionally Table 15 shows U-values of different roof types.

Table 15: Example of Representative values for different wall ceiling and thicknesses (Röster, 2012)

Type	U-Value [W/m²K]	Insulation thickness [cm]
Massive Concrete	2	30
Hollow Part Ceiling	1.4	35
"Dippelbaum" Ceiling	0.5	35
Standard new building	<0.2	-
Standard passive house	< 0.15	-

Improving Insulation - exact methods

In addition to the u-value, other parameters affect the heat loss and gain through walls/roof and floors. For example, the air leakage and the heat transfer resistance at the surfaces. In addition, using real climate data (temperature and solar radiation) will improve the exactness of the estimation.

Detailed, dynamic simulations are supported by building simulation software like TrnSys[21], EnergyPlus[22] or IdaICE[23]. When estimating the effect of insulating houses, two simulations need to be done: one with and one without insulation.

Adding shading

Adding exterior shades has no effect on the U-value of the building but affects the solar gains of a building. This is only the case for exterior shading, interior shading has no such effect unless they have reflective capabilities and thus reflect proportions of the light back

[21] http://www.trnsys.com/
[22] https://energyplus.net/
[23] https://www.equa.se/en/ida-ice

out the window (McCluney and Mills, 1993). The effects of shading can, according to (Tang, 2012)be calculated using the Solar Heat Gain Coefficient (SHGC)

$$SHGC = SHGC_{ext} \cdot SHGC_{int} \cdot SHGC_{glz}, \quad (8)$$

where$SHGC_{ext}$is the heat gain coefficient for external shading, $SHGC_{int}$ the value for internal shading and $SHGC_{glz}$ the value for glazing. The solar heat gain coefficient describes the factor of solar radiation / heat that passes into the buildings. The coefficient can reach values between 0 and 1. The solar heat gain is strongly affected by one's location and the angle at which the sun shines on a building.

According to (Tang, 2012), depending on the type of shading and the angle of the shades values of 0.39 for horizontal shades, 0.7 for vertical shades and 0.33 for combined shades can be reached. For internal shades depending on the type of glazing of the window and the type of internal shade values between 0.25 (white reflective translucent screen in combination with 6 mm single glazing) and 0.94 (dark weave draperies in combination with low-e double glazing windows) can be reached.

4.6. Modelling energy sufficiency

An energy sufficient (Sorrell et al., 2020) place is the state of an environment in which people have access to and consume energy without exceeding environmental limits. This implies self-regulation, self-restriction to a certain sobriety that does not allow for over-consumption.

Where energy efficiency is usually achieved at households through modern and often expensive equipment, energy sufficiency is achieved through low or no-cost interventions, such as behavioural changes or appropriate adjustment of the equipment already in place in the home. The following lists includes the most relevant energy sufficiency actions found in the literature:

- **Set the temperature of the thermostat at the lowest temperature that feels comfortable under well-dressed conditions 18°C[24].** The basic level of warmth required for a healthy, well-dressed person is 18ºC. For healthy persons, high temperature can cause cardiovascular risk, headaches and dry atmospheres which irritate the skin. Please note that well-dressed conditions included using a sweater or similar cloth in winter and shorts (or similar) in summer.
- **Take shorter showers.** Hot water is one of the most energy consuming activities in households.
- **Hang dry your laundry / use the sun to dry the laundry[25]**. Extra care should be taken with this one as drying the laundry indoors could lead to health problems.
- **Unplug unused electronics (such as TVs, computers and video games)**. Standby power can account for 10% of an average household's annual electricity use.
- **Use natural airflow by opening your windows in the morning and block the sun when it is hot in the afternoon with curtains/shutters.** In summer months, keep

[24] https://rointe.com/uk/save-energy-without-losing-comfort/
[25] https://www.trvst.world/inspiration/7-ways-to-save-electricity-at-home/

them closed to prevent the sun from heating up your space and working against your cooling unit. Promote airflow through your home and block the afternoon sun.

A complete list can be found on the Zenodo-Page of the WHY-project[26].

4.7. Modelling energy management systems

Energy Management Systems (EMS) play an important role in the smart energy system concepts facilitating 2 of the main success factors: (1) Information on energy consumption and (2) activation of energy flexibilities. As for the activation of flexibilities, energy management systems use measured data, forecasts and self-learning algorithms, the latter being a quite new approach, to shift flexible loads to times where it is more economic, ecological or convenient to use them.

Today a multitude of different EMS for different ranges of consumers is available and has substantial market potential. The sheer amount of types of energy management systems makes it necessary to cluster them. For the purpose of this Deliverable three clusters were defined: (1) Open Source EMS, (2) Researchers EMS and (3) Commercial EMS.

Next we will provide a brief overview of different types of EMS as a baseline for creating the models in the WHY-Toolkit.

- **OpenEMS**[27] (Open Source, Code written mainly in Java and HTML): Modular platform for energy management applications: monitoring, controlling, and integrating energy storage together with renewable energy sources and complementary devices and services like electric vehicle charging stations, heat-pumps, electrolysers, time-of-use electricity tariffs and more. Code has three main parts/applications: OpenEMS Edge: runs on site, communicates with devices and services, collects data and executes control algorithms, OpenEMS UI is the real-time user interface for web browsers and smartphones and OpenEMS Backend runs on a server, connects the decentralized Edge systems and provides aggregation, monitoring and control via internet.
- **Openremote**[28] (Open Source, Code written mainly in Java, TypeScript and Groovy): Very technical Code which simplifies connecting networked assets to mobile and web applications and therefore can be perfectly used as an energy management system. One can create a dynamic scheme of all available assets and their attributes in the openremote manager. For example, for modelling an internet of things system for a smart home or office one would create Building, Apartment, Room and Sensor assets on the domain. In addition rules can be written in Groovy, JavaScript, Json or Flow model and dynamically deployed. Rules execute actions when matching asset states or sequences of events are detected. For example when humidity in a room keeps increasing, one can notify a group of users via email and on their mobile devices. Assets and devices are connected to the Openremote manager via Agents, which are the API (application programming interface) to 3rd party device software and service protocols. The OpenRemote FrontEnd simplifies

[26] https://zenodo.org/communities/why/?page=1&size=20
[27] https://github.com/OpenEMS/openems
[28] https://github.com/openremote/openremote

the creation and deployment of user interfaces such as home automation control panels and smart city monitoring dashboards.

- **Honda Home Energy Management System**[29] (Open Source, Software ready for installing (no adaptations by users possible): Open-source EMS that works in dwellings that were built to be smart homes, rather than by adding gadgets to a conventional residence. It can monitor, control, and optimize the electricity consumption and generation of the house (batteries, EVs, lights and HVAC systems) Its energy management tools are integrated with the smart grid to respond properly to DR.
- **PowerMatchSuite**[30] (Open Source written in Java, JavaScript, html, shell und python): The Suite comprises two disruptive open source technologies; the PowerMatcher and the Energy Flexibility Platform & Interface. Both technologies are complementary but can also function on their own. The PowerMatcher is a smart grid coordination mechanism. The Energy Flexibility Platform & Interface is an operating system which enables appliances, the smart grid and smart services to communicate with each other. PowerMatcher technology is a distributed energy systems architecture and communication protocol, which facilitates implementation of standardized, scalable Smart Grids, that can include both conventional and renewable energy sources. Through intelligent clustering, numerous small electricity producing or consuming devices operate as a single highly-flexible generating unit, creating a significant degree of added-value in electricity markets. PowerMatcher Technology optimizes the potential for aggregated individual electricity producing and consuming devices to adjust their operation in order to increase the overall match between electricity production and consumption. The Energy Flexibility Platform & Interface (EF-Pi) is a runtime environment where on one side smart grid applications can be deployed and on the other side appliances can be connected, see it as a gateway operating system. The EF-Pi provides interfaces to interact with the environment,such as a User Interface, and connect devices and smart grid apps. Part of the interface definitions are the Control Spaces and Allocations. EF-Pi aims to create an interoperable platform that is able to connect to a variety of appliances and support a variety of DSM approaches.
- **openHAB**[31] (Open Source written in Java, shell, HTML and javascript): openHAB communicates electronically with smart devices, performs user-defined actions and provides web-pages with user-defined information as well as user-defined tools to interact with all devices. To achieve this, openHAB segments and compartmentalizes certain functions and operations: Bindings provide the interface to interact with devices, things are the representation of devices in the software, items contain information about the devices, channels connect things and items and rules perform automatic actions. Sitemap is the user interface that presents the information and allows for interaction.
- **Home Assistant** (Open Source EMS): An open source home automation with a strong focus on local controls and privacy. It can be run for instance on a Raspberry Pi and provides the option for Observation, Control and Automation of devices. Since it is developed by a large open community, multiple different devices of different brands can be connected.

[29] https://www.hondasmarthome.com/tagged/hems
[30] https://github.com/flexiblepower
[31] https://github.com/openhab

- **EnergySniffer** (Research EMS) (Uddin and Nadeem, 2012): EnergySniffer is a simple and flexible energy monitoring system that utilizes smartphone sensors. EnergySniffer exploits sensors such as magnetic sensors, light, microphone, camera, and WiFi in smartphones to detect and monitor each operating machine in its vicinity. Energy Sniffer consists of two parts:
    - Energy Profile is a database containing machines with their corresponding energy consumption profiles. Energy Profile is maintained as a web service instead of storing it locally on the phone.
    - The multi sensing framework consists of Offline Learning and Online Detection Phases. Offline learning is responsible for building fingerprint profiles for each individual machine. Online detection uses the fingerprint profiles to detect and monitor operating machines.

  In building fingerprint profiles the relevant sensors (acoustic, Bluetooth, WiFi, …) of the machine are identified and data from the sensors is collected and combined. In the online Detection and Monitoring Phase a machine learning algorithm is used to detect and monitor running machines. Once the system detects a machine, it uses the Energy Profile database to track the energy consumption of the machine.
- **ALIS** (Research EMS) (Rodgers and Bartram, 2010): ALIS focuses on engaging occupants in conservation efforts. The Aware Living Interface System (ALIS) encourages conservation in daily activities by creating awareness of resource use and facilitating efficient control of house systems. ALIS is an integrated in-home support system. In contrast to the vision of a smart home populated with intelligent communicating devices, ALIS focus is set on the aware home with support for the smart occupant. ALIS is composed of three layers: house systems and resource infrastructure, software comprising a custom control system and web server, and user interfaces on several platforms: embedded touch panels, mobile and personal computers, and informative art. Users are free to enter an optimized energy use state based on input from environmental sensors. In addition, users can enter custom energy optimizing nodes, like for example turning off most lights and lowering the thermostat in Sleep mode or eliminating standby power draws in Away mode. The main goal is to make energy-saving behaviour easy to enact. ALIS also provides a variety of feedback displays and analytical tools. Historical, real-time, and predicted information on resource production and consumption is available.
- **Autonomous demand-side management** (Research EMS) (Mohsenian-Rad et al., 2010): Autonomous and distributed demand-side energy management system among users that takes advantage of a two-way digital communication infrastructure. Game theory is used to formulate an energy consumption scheduling game, where the players are the users and their strategies are the daily schedules of their household appliances and loads. It is assumed that the utility company can adopt adequate pricing tariffs that differentiate the energy usage in time and level. The proposed distributed demand-side energy management strategy requires each user to simply apply its best response strategy to the current total load and tariffs in the power distribution system. The users can maintain privacy and do not need to reveal the details on their energy consumption schedules to other users. Simulation results confirm that the proposed approach can reduce the peak-to-average ratio of the total energy demand, the total energy costs, as well as each user's individual daily electricity charges.

- **Intelligent Home Energy Management (**Research EMS) (Pipattanasomporn et al., 2012): The intelligent EMS algorithm manages high power consumption household appliances with simulation for Demand Response (DR) analysis. The proposed algorithm manages household loads according to their preset priority and guarantees the total household power consumption to be below certain levels. Considered appliances: space cooling units, water heaters, clothes dryers and Electric Vehicles (EVs).
- **Energy Elephant**[32] (Commercial EMS): Automated data insights, import of historical data, sensor data, track of fuel usage, building performance comparison, support for energy investment decisions, greenhouse gas tracking, sustainability guide, energy price analysis and cost reporting
- **Energy Sparks**[33] (Commercial EMS): Energy Sparks enables the user to perform energy analysis and has a reporting application for electricity, alternative energy generation (solar, storage), natural gas, oil and water. Available data acquisition connectors: Bacnet IP, Modbus TCP, Obix, Haystack, SNMP, Sedona, OPC UA, MQTT, SQL, CSV import (manually or batched), REST API
- **Home iOs**[34] (Commercial EMS): Scheduling and control via app (from everywhere): air conditioning, air cleaning, bridges, cameras, bells, water, doors, ventilation, dehumidifier, lights, locks, sockets, receiver, router, security systems, speakers, sensors, switches, lawn sprinklers, TV, windows, thermostat. Notifications in case of certain events (children come home, somebody is at the door, temperature decreases, …) Focus not so much on reducing energy consumption (still it can be done this way). Focus on control from everywhere, comfort and fancy installations
- **Eagle 200 – rainforest automation**[35] (Commercial EMS): Eagle 200 enables the user to monitor data from smart meters and connected devices and is able to control "On/Off''-devices. It facilitates the ZigBee Connection for communication between the devices and central hub.
- **Opinum**[36] (Commercial EMS): Opinum enhances, analyses, centralises and visualizes energy related data using a secured cloud-based platform. Devices can be connected to metadata from the cloud to improve event detection (internet of things, etc.). Data processing can be automated by existing and personally developed algorithms (mainly machine learning), visualization and reports, REST API connections

4.8. Modelling energy storages

Energy storages play a crucial role to provide the energy system with the necessary flexibility to mitigate the negative side effects of an increasing amount of variable renewable energy sources in the energy system.

Modelling energy storages comes down to two parts. Firstly the mathematical representation of the storage system itself, meaning the formulas which describe the technical behaviour of the system and secondly the model describing the control strategy of the storage system and its links to other systems. Meaning the strategy which decides

[32] EnergyElephant : Make Better Energy Decisions
[33] https://energyelephant.com/
[34] https://www.apple.com/de/ios/home/
[35] https://www.rainforestautomation.com/rfa-z114-eagle-200-2/
[36] https://www.opinum.com/

when the storage system is charged and when it is discharged. The models for the second part are treated in Section 3.7, this chapter specifically focuses on the different types of storage systems relevant for households and how to model them.

The storage systems considered in this study are clustered according to the technology used. The relevant clusters are:

- Electro-Chemical Storages
  - Classical Batteries
    - Li-Ion Technology
    - Nickel Cadmium Technology
    - Nickel Metal Hydride Technology
    - Zinc-Air Technology
    - Sodium Sulfur Technology
    - Sodium Nickel Chloride Technology
    - Lead Acid Technology
  - Flow Batteries
    - Vanadium Redox Flow Technology
    - Hybrid Flow Technology
- Chemical Storages
  - Hydrogen
  - Synthetic natural gas
  - Biomethanation
- Mechanical
  - Flywheel
  - Pressure
- Electrical
  - Supercapacitator
  - Superconducting Magnetic
- Thermal
  - Sensible Heat
  - Latent Heat
  - Thermo Chemical

The next paragraphs set the technical representation of the storage system. Rather than trying to provide different modeling approaches for each technology, the models presented here show basic simulation approaches valid for different technologies. The approaches differ in the simplifications applied or the degree of detail employed.

- **Battery**
  - **Container Model** (Widl et al., 2019): Electrochemical processes within the battery are simplified to a container model: The container is filled - the battery is charged - with a given charging efficiency. The container is emptied - the battery is discharged - with a given discharge efficiency. The size of the container - the capacity of the battery - is limited. The model may also consider maximum and minimum charging and discharging power, as well as aging effects of the battery, which reduce the capacity. In general, the container model is perfectly suited for sketchy simulations, which have to be cheap in terms of computation time.

- **Open Circuit Model** (Omar et al., 2014), (Plangklang and Pornharuthai, 2013), (Marra et al., 2012), (Widl et al., 2019)**:** The battery is modeled as an equivalent circuit with various resistances and impedances connected in series. The open circuit model approximates the electrochemical processes within the battery and provides a realistic representation of it. This representation yields a mathematical link between the state of charge, the current, and the voltage of the battery, which is given by differential equations (number and order depend on the choice of the open circuit representation). In general, the accuracy of the model increases with the number of impedances included in the model. Often, the choice of a first order circuit, which contains one capacitor and one resistance only, already provides good results. The battery voltage depends on the state of charge of the battery itself. This correlation can be either described by Open Circuit Voltage (OCV) lookup tables, or by empirical laws. An OCV lookup table contains characteristic values for the open circuit battery voltage dependent on the State of Charge (SOC). Each battery type has a characteristic OCV lockup table which can be used as model input. Alternatively, empirical laws approximate the correlation of the open circuit voltage and the state of charge by simple fitting function (mostly a constant term, an exponential term, and a friction term). The fitting parameters can be either defined from measured curves or estimated from known parameters. In addition, the temperature dependence of the state of charge and the age dependence of the capacity are given by empirical laws. Depending on the choice of model, the approach results in a more or less detailed, dynamic model with the negative side effect of higher simulation times.
- **Microscopic Models** (Jongerden and Haverkort, 2009)**:** The electrochemical processes in batteries can be modelled as a diffusion process or a kinetic process. A diffusion process describes the evolution of the concentration of electroactive species in electrolytes to predict the state of charge under a given load. Diffusion processes in batteries are described by Fick's law (partial differential equations, which can be solved analytically by application of a Laplace Transformation). In the kinetic process battery charge is distributed over two wells: the available charge well and the bound charge well. The available charge well supplies electrons directly to the load, whereas the bound charge well supplies electrons only to the available charge well. The rate at which charge flows between the wells depends on the height difference between the two wells and the conductance. Also this system is described by two partial differential equations, which can be solved analytically by application of the Laplace transform. Dualfoil[37] is an open source Fortran program, which also suits this category: batteries are simulated using the principles of concentrated solution theory, porous electrode theory, Ohm's law, Butler - Volmer kinetics, current-, and mass conservation. Due to its high accuracy in representing the battery internal electrochemical process, it is widely used by researchers to validate other models.

- **Chemical Storage**

[37] http://www.cchem.berkeley.edu/jsngrp/fortran.html

- **Hydrogen Storage Model** (Al-Refai, 2014)**:** The compression for storing hydrogen is described by an isothermal process, where the hydrogen is assumed to be an ideal gas. Either one compression is modelled or a multistage compressor, which conducts more compressions in a row is included in the model. High pressure hydrogen gas storages, and metal hydride storages are included in the HYDROGEM library, which was originally developed by a PhD student and then further improved by a whole community. It is compatible with TranSys and contains other hydrogen component models like advanced alkaline water electrolysis, proton exchange membrane fuel cells, alkaline fuel cells, compressors, and power conditioning equipment. In addition, hydrogen storage models can be implemented in the Matlab/Simulink environment. The model is mainly used in engineering environments, where the hydrogen storage is coupled to many other components of an integrated system (e. g. photovoltaic, electrolysis or fuel cells).
- **Modelling Methanation** (Tilla and Dace, 2016), (Perna et al., 2020)**:** Hydrogen can be fed into the natural gas grid and stored that way. The methanation process can be split into two parts: the process in a mixing and preheating tank and the process in the methanation reactor. $C0_2$ based methanation is modeled assuming chemical equilibrium and adiabatic conditions. The chemical reactions are mainly described by four adiabatic reactors connected in series with intermediate gas cooling. The chemical reactors can be simulated using RGibbs operation block, where the chemical equilibrium of a given set of species is solved through the minimization of the Gibbs free energy. The model focuses on the description of chemical processes and the calculation of reaction rates.

- **Mechanical Storage**
  - **Flywheel Model** (Wencong Su et al., 2010), (Stas et al., 2020)**:** An electric motor is used to drive a flywheel and later on the rotating flywheel is used with the motor as generator to produce electricity. In general, a flywheel has three operational phases: the driving phase, where energy is put into the flywheel to accelerate it, the storing phase, where the flywheel is constantly rotating with small losses, and the producing phase, where electricity is generated and the flywheel is slowed down. The mechanical relations of the system are described by four coupled first order differential equations or by two coupled second order differential equations. The electromagnetic processes can be modeled by Matlab/Simulink, where the flywheel is coupled with a built-in motor/generator, which is modeled as a permanent magnet synchronous machine. Alternatively, the system can be described analytically. For the analytical solution the angular velocity has to be linearized and complex analysis is indispensable. As the flywheel cannot be driven with the maximum frequency from the very beginning, an AC/AC converter is needed to gradually increase the rotational frequency. The same holds true for electricity generation driven by the flywheel. An AC power converter is modeled by space vector pulse width modulation (SVPWM).
- **Electrical Storage**
  - **Supercapacitor - Open Circuit Model** (Cultura and Salameh, 2015), (Krpan et al., 2021): The model uses an equivalent circuit model (see Figure X). The

capacitance of the capacitor is dependent on the applied voltage. This is accounted for by modeling the capacitor by two parallel capacitors. One with constant capacitance (C0), and one which capacitance varies linearly with the applied voltage (C). Resr is the equivalent series resistance that contributes to the energy loss during charging and discharging of a supercapacitor. Rp is the equivalent parallel resistance that simulates energy loss due to supercapacitor self-discharge. The order of the open circuit model can be increased to improve the accuracy of the description. Using fundamental physical laws, differential equations, which describe voltages and currents across the supercapacitor, are derived and solved.

- **Superconducting Magnetic Energy Storage Models** (Sahoo et al., 2015), (Chen et al., 2006)**:** A superconducting magnetic energy storage (SMES) is a direct current (DC) device that stores energy in the magnetic field. It consists of several subsystems: The heart of the SMES system is a large superconducting coil which is used to store energy. It is contained in a cryostat, which is necessary to keep the temperature well below the critical temperature for the superconductor. An AC/DC power conversion or conditioning system (PCS) is used to charge and discharge the coil. A transformer provides the connection to the power system and reduces the operating voltage to acceptable levels for the power conditioning system. Additionally, a magnet protection system has to be installed to detect abnormal conditions that may cause a safety hazard to personnel or damage to the magnet. A detailed model of the SMES implies lumping each component, which results in complex circuit diagrams, which can be solved e. g. in Matlab/Simulink or PSCAD/EMTD.

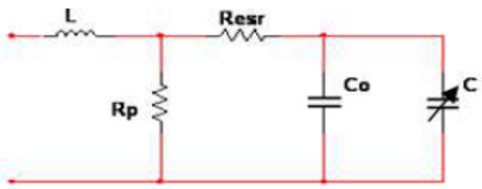

Figure 2: Model representation of the Open Circuit Model (Cultura and Salameh, 2015)

- **Superconducting Magnetic Energy Storage - simplified model** (Chen et al., 2017)**:** A simplified model of the superconducting magnetic energy storage (SMES) disclaims the DC-AC converters and concentrates on the dynamic energy exchange between the magnet and the external power system. The electrical circuit model of the simplified case is shown below. It includes a superconducting coil L, a snubber capacitor C, two power diodes D1 and D2, two power switches S4 and S5, and a persistent current switch (PCS) S6, which can be used to simulate the initial response time of the direct current (DC) SMES system while charging or discharging. The model is translated into a mathematical model, which results in a set of differential equations describing the dynamics of the system.

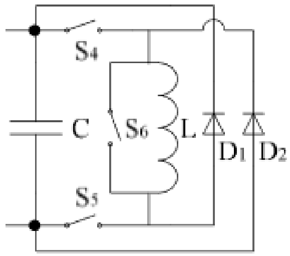

Figure 3: Model representation of the simplified model (Chen et al., 2017)

- **Thermal Storage**
  - **Sensible Thermal Storage - Container Model** (Steen et al., 2015)**:** The model assumes a fully mixed tank with constant pressure and a constant volume. It describes a container full of energy, which is the analogon to a tank full of liquid with temperature varying in time: The heat energy contained in the tank is defined by the volume of the storage, the actual average temperature of the liquid, and its heat capacity. Assuming a simplified process, heating the fluid in the storage is described by simply adding energy with a given efficiency. Supplying heat to external loads is described by subtracting energy with a given efficiency. General heat losses are calculated with an overall u-value. The maximal temperature of the liquid determines the capacity of the storage. The model neglects thermal dynamics within the storage and is not very accurate. Its strength lies in its simplicity and little computational effort.
  - **Sensible Thermal Storage - Variable Volume Model** (Klein et al., 2017)**:** An alternative to the energy container model is the variable volume model, which considers a fully mixed tank with constant pressure and constant temperature. The tank is filled with liquid of variable volume. The tank volume defines the storage capacity. In its simplest form, a single flow enters from a hot source and adds more volume to the tank. Another flow stream exits to a load and subtracts volume from the tank. Since the incoming and outgoing flows do not have to be equal, the level of fluid in the tank can vary. The model neglects thermal dynamics and is not very accurate. In addition, supply temperatures can not be varied within the model. The strength lies in the model simplicity.
  - **Sensible Thermal Storage - Stratified Model** (Klein et al., 2017), (Widl et al., 2019), (Bastida et al., 2019): The model describes the thermal dynamic behaviour within a water tank. It accounts for the temperature differences and the resulting heat transfer in the storage. The model is based on a computational fluid dynamics approach: Energy balance is formulated which results in a partial differential equation. Because of its complexity, it is discretized using thermal stratification: The tank is horizontally split into levels, where each level is considered to be in equilibrium. Then, heat transfer occurs only between the different layers. The discretized system is described by a set of ordinary differential equations. The more layers are chosen, the higher the accuracy of the model. The model of the storage itself is often combined with heat exchangers, which add energy to the lowest (coldest) temperature level and extract energy from the highest (hottest) temperature level. These processes are also described by heat

transfer. The heat loss from the storage to the environment is characterized by an overall u-value. Conventionally, the tank has a fixed volume. Thus, the same mass flow injected at the top of the tank leaves the tank at the bottom and vice versa. The model is commonly used in technical simulation environments like TranSys, Modelica or Matlab. It can be extended to models, which treat other storage media than water (e.g. oil)

- **Sensible Thermal Storage - 3D model** (Terzibachian et al., 2016): The model accounts for the thermal dynamic behaviour within a heat storage without dicretisations and simplifications: The model predicts 3D fluid motion in a thermally isolated cylindrical tank as well as the temperature profile variation. The model is based on a computational fluid dynamics (CFD) approach. Energy balance and mass balance are formulated and the partial differential equations are solved without discretisation, so that temperature and pressure as well as their gradients are described by continuous field variables. The 3D-CFD model is accurate, with the drawback that it requires large computational resources and computing times. In addition, it is limited in terms of coupling with models from different simulation domains.
- **Latent Thermal Energy Storage Model** (Pan, 2019), (Cao et al., 2013), (Scharinger-Urschitz, 2019)**:** Latent thermal energy storages (LTES) use phase transitions of PCM (phase change materials). When heating up a solid material, at the melting point non-linear behaviour is observed: latent heat is consumed in order to enable the phase transition. This effect is illustrated in Figure 4, where one can see that the specific heat shows a peak at the melting point and the enthalpy suddenly increases to a higher level. The absorption of latent heat leads to extremely high energy densities, when PCMs are used as heat storages. The challenge in modelling LTES is that during a phase change mostly both phases (solid and liquid) exist at the same time, and the temperature is not exactly the same everywhere in the storage. This situation can be mathematically described by a boundary value problem for a partial differential equation, which aims to describe the temperature distribution in a homogenous medium undergoing a phase change. The equation includes one derivative with respect to time and one second order derivative with respect to space, which makes the solution dependent on the geometry of the storage. The most popular solution to the mathematical problem is a discretisation in time and space which allows the application of a finite element method to maintain a solution. This approach is referred to as the enthalpy method.

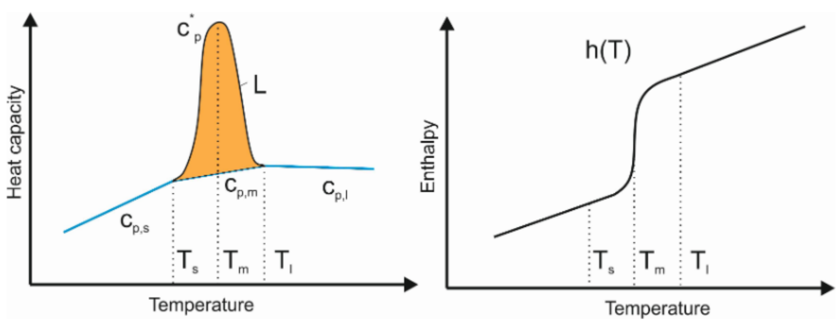

Figure 4: heat capacity (left) and enthalpy (right) during the melting process

4.9. Modelling HVAC systems

The Heating, Ventilation and Air Conditioning (HVAC) systems generally have a substantial potential for a) providing flexibility to the energy system and b) contributing to the energy efficiency of a building. In terms of mathematical modelling and simulation, three parts need to be considered: (i) HVAC components, (ii) HVAC control and (iii) HVAC systems in general, this is similar to the simulation of the storage system. Additionally, when it comes to thermal stores, they are a crucial part of the HVAC components but will not be described in this chapter, since they are already mentioned in the chapter above.

The HVAC components describe the individual parts of the HVAC System that contribute to heating, cooling or ventilation. The HVAC control is, as is the case for storage systems, the control mechanism which decides when the devices work as well as the working parameters. The HVAC system in general described how the different components are linked together within the building.

As with storage systems, the WHY-consortium tries to provide an overview of the different modelling approaches for HVAC devices of the following categories

- Tankless Heating
- Electric or Resistance heating
- Gas boiler heating
- Air Conditioning
- Ventilating

While the consortium is well aware that this list is not exhausting, it is a good indication of the most relevant technologies available. Within each of the categories multiple different models will be considered for further use in the WHY-project.

Furthermore toolboxes which allow to simulate the HVAC system will be presented. These toolboxes contain the different HVAC devices as single model blocks.

The next paragraphs provide a brief overview of the models identified. The list provided here is by no means exhaustive but aims at creating a better understanding of the modelling approaches and provides crucial inputs for the decision on what models to apply in the WHY-Toolkit.

- **Tankless Heating (gas boiler and electric resistance)**: Tankless water heaters heat water directly without the use of a storage tank. When a hot water tap is turned on, cold water travels through a pipe into the unit. Either a gas burner or an electric element heats the water. There are several computer simulation models for water heaters. The most comprehensive general models are TANK (Paul et al., 1993) [2], WATSIM (Hiller et al., 1994) or HEATER (Little (Arthur D.), Inc. and Cambridge, MA (USA), 1982). However, these earlier models focus on tank temperature spatial distribution and are therefore not well suited to model tankless instantaneous heaters. Other water heater models have been built using TRNSYS and similar general-purpose computer simulation tools (Lutz et al., 2013).

  Detailed dynamic models mostly consist of the simulation of individual parts of each internal component, describing thermal, fluid and mechanical dynamics. The models of each component are interconnected, creating Tankless water heating devices with different hardware configurations that could be parameterized differently. In (Quintã et al., 2019) for example a lumped space approach was used to model individual components. The lumped system analysis was preferred over distributed analysis, considered through a finite element or finite difference methods, in order to meet the requirements for implementation of predictive control algorithms in computationally limited embedded systems. The mathematical models result from the application of physical laws that describe, with small deviations, the dynamics of the system. For the heat cell, a semi-empirical model was used. The individual components considered for modelling are a pipe, split, junction, reservoir, valves and heat cell. Each component is modelled considering a control volume, for which mass and energy conservation equations are established. The thermal component is detached from the fluidic part.

- **Air Conditioning:** To model air conditioning there are several libraries available in TRNSYS, Modelica, Matlab or similar programmes (see below). As there are many different devices, it is hard to compare the simulation methods in general. The simulation models however can be differentiated depending on their degree of detail and on their focus. On the one hand there are models which focus on the building model (room climate) and on the other hand there are detailed models of one specific device. Some models which are focused on the room climate do not model the devices but only consider a certain power for cooling for example. The best results will of course be achieved if a detailed building model is combined with detailed models of air conditioning devices. All three above mentioned programmes allow such detailed dynamic simulation.

- **Ventilating:** As for the air conditioning the building model is the key element to model ventilation systems. The used methods can again be separated depending on their degree of detail. Simple ventilation models are often only considering one zone (room) and calculate the ventilation depending on the air exchange rate which can be defined by the user (constant or as a time series).

  Detailed multi zone airflow models normally consist of nodes that are connected by flow elements. The nodes may represent room air volumes, the exterior environment or connections in a duct system and contain state variables, typically pressure, temperature and concentrations such as water vapor, CO_2, smoke or pollen. The flow elements are airflow paths such as open doors and windows, construction cracks, stair cases, elevator shafts, ducts and fans. Multizone airflow models are typically used for time domain simulation of convective energy and contaminant transport between thermal zones of a building and to quantify stack effects in high rise buildings. For thermal building simulation, the closed door and user-estimated airflows that are common practice in most multizone simulations are a poor representation of reality[38].

  Detailed multizone airflow models are for example available in TRNSYS (e.g. TYPE 56 (McDowell et al., 2003)) or in Modelica. Older well known building models are CONTAM, developed by the National Institute of Standards and Technology (NIST)

[38] openmodelica.org

and COMIS, developed in 1988-89 in an international context within IEA Annex 23 at the Lawrence Berkeley National Laboratory (LBNL). Both are implemented in TRNSYS.

- **Matlab [Models for the general HVAC system][39]:** A commonly used option for setting up HVAC systems is the Matlab simulation environment Simscape where one can build physical component models based on physical connections which are directly integrated with block diagrams and other modeling paradigms. It allows for different model systems such as different HVAC devices to be assembled into a working system. Simscape offers a wide variety of different components that can be used to increase the simulation's quality and analysis possibilities. As such Matlab comes with pre-defined blocks for simulating different HVAC devices:
    - **Building Ventilation[40]**: This predefined model for a ventilation circuit within a building works by dividing the air volume inside a building in four distinct zones Each of the different zones performs a different task. For instance Zone 4 which has a "door" which can be opened to vent air out to the atmosphere. Between the zones airflows and exchanges can be established. Each Zone is described by a sub-system which represents the thermal resistance of the Zone. Considering thermal masses of walls, roofs as well as the Convection and Conduction. The ventilation system itself is represented by an internal air source and an external air source, both with limiters that can be applied. The actual air flow is controlled via the flow control.
    - **Thermal Liquid Components[41]**: This library of HVAC devices contains models for Actuators, Pipes and Fittings, Pumps and Motors, Tanks and Accumulators, Utilities as well as Valves and Orifices. Each of the components is described by sets of equations describing the behaviour of the component.
    - **Thermal building blocks[42]**: Modelling components that represent the different thermal aspects of a building that need to be considered when simulating HVAC systems. Components include thermal mass, various heat transfer blocks, etc.
    - **Heat Exchanger Solver** (Seyyed, 2021): For HVAC general systems that contain heat exchangers, this modelling component provides a solver able of calculating outlet temperatures of a Heat Exchanger using the Epsilon-NTU method
    - **Moist Air library[43]:** This library contains basic elements, such as reservoirs, chambers, and pneumatic-mechanical converters, as well as sensors and sources. Use these blocks to model HVAC systems, environmental control systems, and other similar applications. Relevant industries include automotive, aerospace, building.
    - **Thermosys Toolbox[44]:** This toolbox provides the possibility to make simulations in Simulink or Matlab of air-conditioning and refrigeration systems. The toolbox is capable of performing both steady state simulations and time-dependent simulations. The suite consists of a number of Simulink

[39] https://de.mathworks.com/help/releases/R2017a/physmod/simscape/simscapeblocklist.html
[40] https://de.mathworks.com/help/physmod/simscape/ug/building-ventilation.html?s_tid=srchtitle
[41] https://de.mathworks.com/help/physmod/hydro/referencelist.html?category=thermal-liquid-modeling
[42] https://de.mathworks.com/help/physmod/simscape/thermal-elements.html?s_tid=CRUX_lftnav
[43] https://de.mathworks.com/help/physmod/simscape/ug/modeling-moist-air-systems.html?s_tid=srchtitle
[44] https://de.mathworks.com/products/connections/product_detail/thermosys.html?s_tid=srchtitle

blocks which are appropriate for either independent use or integration into larger Simulink simulations. Each block has user-tunable parameters to allow better simulation of practical systems.
    - **CARNOT Toolbox[45]:** is a toolbox extension for SIMULINK. It is a tool for the calculation and simulation of the thermal components of HVAC systems with regards to conventional and regenerative elements. The CARNOT Toolbox is a library of typical components of these systems. It is organized in Blocksets like the SIMULINK Library itself. The handling of the blocks is exactly the same as in SIMULINK, so that users familiar with SIMULINK can directly use the new Blocksets in the same way.
- **Modelica [Models for the general HVAC system]:** Modelica is a simulation environment similar to Matlab, which is composed of different libraries that represent different parts of the HVAC system:
    - **Modelica.Fluid.Examples.HeatingSystem[46]:** This Modelica Library contains a simple exemplary heating system with a closed flow cycle. During the simulation a valve is used to regulate the heating system, as means of a simple control. This example underlies some assumptions and simplifications such as perfect isolation of the pipes and negligence of pressure losses between heater and pipes.
    - **HVAC library** (Burhenne et al., 2013)**:** This library allows the development and optimisation of large thermo-hydraulic HVAC systems. It provides the user with the possibilities to use components such as Air ducting, Adiabatic and steam humidifiers and water extractors, Borehole heat exchanger, Absorption- and vapor compression chillers, Evaporative and dry cooling towers, Boilers and combined heat and power, Heat pumps, Heat exchangers (liquid and air side), etc. The library can be used to simulate multiple different layouts of HVAC systems in different building settings.
    - **Hydronics Library[47]**: This library contains all the components necessary for a detailed model of thermo-hydraulic systems including heat exchangers for humid air and liquids. All components like pipes,bends, pumps and valves can be insulated, non-insulated or adiabatic. Joints, orifices, sudden expansions, contractions and expansion vessels complete the range of model components.
    - **TIL – Model library[48]:** This Library (which is not exclusively limited to Modelica) contains many different components and models. It allows the detailed analysis of individual components or to put together multiple components to form larger HVAC systems. Amongst others the library can be used to simulate (Refrigeration cycles, including refrigeration mixtures, Heat pump systems, Systems with ejectors, Hydraulic networks etc.). Furthermore the library can be combined with the TILMedia Suite to allow an efficient calculation of thermophysical properties of liquids, gases, real fluids containing a vapor liquid equilibrium and mixtures.
    - **AixLib[49]:** AixLib is an open-source model library for Modelica which allows building performance simulations. It contains Modelica models for the

[45] https://de.mathworks.com/matlabcentral/fileexchange/68890-carnot-toolbox?s_tid=srchtitle
[46] https://build.openmodelica.org/Documentation/Modelica.Fluid.Examples.HeatingSystem.html
[47] https://www.claytex.com/products/dymola/model-libraries/hydronics/
[48] https://www.tlk-thermo.com/index.php/en/til-suite
[49] https://github.com/RWTH-EBC/AixLib

building envelope and HVAC equipment such as boilers, radiators, heat pumps and CHPs.

- **BuildingSystems**[50]: This open-source library for Modelica for dynamic simulations of the energetic behaviour of a wide range of purposes ranging from single rooms to whole districts. Building envelopes are modeled by a dynamic energy balance including boundary conditions such as ambient climate and user behaviour.
- **BuildSysPro**[51]**:** This free and open-source Modelica library provides the possibility to simulate both the building envelope and HVAC system within the building. It can simulate air flows and also provides control algorithms for the devices.
- **Buildings.Fluid.HeatPumps**[52]**:** This library contains all the elements needed to simulate heat pumps with a very high degree of technical details. The library provides the models for different types of heat pumps.
- **Modelica.Electrical.Analog.Basic.HeatingResistor**[53]**:** This is a model for an electrical resistor where the generated heat is dissipated to the environment via connector heatPort and where the resistance R is temperature dependent.
- **Buildings.Fluid.Boilers – Modelica Library**[54]**:** This package contains components models for boilers.
- **BuildSysPro.Systems.HVAC.Production.Boiler.Boiler:** It is a dynamic model of modulating condensing boiler. The gas consumption prediction model is estimated with a grey box model. Electric consumption is determined according to the consumption[55] of the various operation phases of the boiler (purging, pump, power on/off, standby, etc). This model requires a limited amount of input data accessible from the normative tests.
- **Air conditioning library**[56]**:** The Modelica Air Conditioning Library is used to design, analyze and optimize automotive air conditioning systems during early design stages. It comes with both ready-to-use refrigeration cycle templates and a wide range of components to create non-standard configurations.

- **TRNSYS Models [Models for the general HVAC system]:** TRNSYS is the abbreviation for Transient System Simulation Tool, a very potent environment to simulate complex energy systems. The simulation tool contains multiple different libraries and tools to simulate different HVAC components, as is shown below.
  - Type753 models a heating coil using one of three control modes. The heating coil is modeled using a bypass approach in which the user specifies a fraction of the air stream that bypasses the coil. The remainder of the air stream is assumed to exit the coil at the average temperature of the fluid in the coil. The air stream passing through the coil is then remixed with the air stream that bypassed the coil. In its unrestrained (uncontrolled) mode of operation, the coil heats the air stream as much as possible given the inlet

[50] https://modelica-buildingsystems.de/index.html
[51] https://build.openmodelica.org/Documentation/BuildSysPro.html
[52] https://simulationresearch.lbl.gov/modelica/releases/latest/help/Buildings_Fluid_HeatPumps.html
[53] https://doc.modelica.org/om/Modelica.Electrical.Analog.Basic.HeatingResistor.html
[54] https://simulationresearch.lbl.gov/modelica/releases/latest/help/Buildings_Fluid_Boilers.html
[55] https://build.openmodelica.org/Documentation/BuildSysPro.Systems.HVAC.Production.Boiler.Boiler.html
[56] https://www.modelon.com/library/air-conditioning-library/

conditions of both the air and the fluid streams. The model is alternatively able to internally bypass air around the coil so as to maintain the outlet air dry bulb temperature above a user specified minimum, or to maintain the fluid outlet temperature above a user specified minimum.

- TYPE 917: AIR-TO-WATER HEAT PUMP - This component models a single-stage air source heat pump.
- TYPE 919: NORMALIZED WATER SOURCE HEAT PUMP - This component models a single-stage liquid source heat pump with an optional desuperheater for hot water heating.
- TYPE 922: TW0-SPEED AIR-SOURCE HEAT PUMP (NORMALIZED) - Type922 uses a manufacturer’s catalog data approach to model an air source heat pump (air flows on both the condenser and evaporator sides of the device).
- TYPE 927: NORMALIZED WATER-TO-WATER HEAT PUMP - This component models a single-stage water-to-water heat pump.
- TYPE 941: AIR-TO-WATER HEAT PUMP - This component models a single-stage air to water heat pump.
- TYPE 954: AIR-SOURCE HEAT PUMP/SPLIT SYSTEM HEAT PUMP - Type954 uses a manufacturer’s catalog data approach to model an air source heat pump (air flows on both the condenser and evaporator sides of the device.
- TYPE 966: AIR-SOURCE HEAT PUMP – DOE2 APPROACH - Using the approach popularized by the DOE-2 simulation program, the performance of an electric air-source heat pump can be characterized by bi-quadratic curve fits.
- TYPE 1221: NORMALIZED 2-STAGE WATER-TO-WATER HEAT PUMP - This component models a two-stage water-to-water heat pump.
- TYPE 1247: WATER-TO-AIR HEAT PUMP SECTION FOR AN AIR HANDLER - This component models a single-stage liquid source heat pump.
- TYPE 1248: AIR-TO-AIR HEAT PUMP SECTION FOR AN AIR HANDLER - Type1248 uses a manufacturer’s catalog data approach to model an air source heat pump (air flows on both the condenser and evaporator sides of the device.
- TYPE 930: ELECTRIC HEATING COIL
- TYPE 663: ELECTRIC UNIT HEATER WITH VARIABLE SPEED FAN AND PROPORTIONAL CONTROL - Type663 models an electric unit heater whose fan speed and heating power are proportionally and externally controlled.
- TYPE 664: ELECTRIC UNIT HEATER WITH VARIABLE SPEED FAN, PROPORTIONAL CONTROL, AND DAMPER CONTROL - Type664 models an electric unit heater whose fan speed, heating power, and fraction of outdoor air are proportionally and externally controlled.
- TYPE 929: GAS HEATING COIL - Type929 represents an air heating device that can be controlled either externally, or set to automatically try and attain a set point temperature, much like Type6 does for fluids.
- TYPE 967: GAS-FIRED FURNACE – DOE2 APPROACH - In this model, the performance of a forced-air furnace is characterized by a constant heat input ratio.
- TYPE 696: AIR STREAM CONDITIONING DEVICE - Type696 models a simple air conditioning device that adds or removes sensible and latent energy

from an air stream to meet user-specified set point conditions of temperature and / or humidity.
  - TYPE 651: RESIDENTIAL COOLING COIL (AIR CONDITIONER) - Type651 models a residential cooling coil, more commonly known as a residential air conditioner.
  - TYPE 508: COOLING COIL WITH VARIOUS CONTROL MODES - Type508 models a cooling coil using one of four control modes.
  - TYPE 752: SIMPLE COOLING COIL - Type752 models a cooling coil using a bypass fraction approach.
  - TYPE 921: AIR CONDITIONER (NORMALIZED) - The component models an air conditioner for residential or commercial applications.
  - TYPE 923: TW0-SPEED AIR CONDITIONER (NORMALIZED) - The component models a two-speed air conditioner for residential or commercial applications.
  - TYPE 697: PERFORMANCE MAP COOLING COIL - Type697 models a simple air cooling device that removes energy from an air stream according to performance data found in a combination of three external data files and based upon the flow rates and inlet conditions of the air stream and a liquid stream.

4.10. Modelling generation technologies

As decentralised generation capacities become ever more important, it is also necessary to provide possibilities to simulate them in order to fully represent “energy behaviour” on household level. For this purpose the following technologies are considered, other technologies were neglected due to a lack in significance for the household energy sector (run of river plants, offshore wind, etc.) :

- PV-generation
  - Roof-Top PV
  - Facade PV
  - Bifacial PV
- Wind-Turbines (only small-scale turbines are relevant for buildings)
- CHP-Technologies
  - Gas powered CHP
  - Hydrogen powered CHP (fuel cell)

The next paragraphs provide an overview of different modelling approaches for the energy sources mentioned above.

- **5 parameter model [Photovoltaic]** (Ete, 2009), (Jovan et al., 2019), (Jumaat et al., 2019), (Ayaz et al., 2014))**:** The photovoltaic array model is based on an equivalent circuit of a one diode model (see in Figure Z). The diode model is described by five formulas for the photocurrent I_L, the saturation current I_D, the reverse saturation current I_S, the current through the shunt resistor I_{sh} and the output current I. For that reason it is also referred to as the five parameter model. The photo current, the saturation current and the reverse saturation current depend on cell temperature and irradiance. These dependencies are given by empirical laws.

Some models assume that the cell temperature was equal to the ambient temperature, others use additional empirical laws to deduce the cell temperature from ambient temperature, incident radiation, wind velocity, and the array type, which can be either monocrystalline, polycrystalline or based on thin film technology.

In addition to the model of the PV, calculations of the solar position are necessary, to project the global radiation on a horizontal plane to the yield on a PV array with given tilt and given orientation. Various methods exist to separate direct radiation from diffuse radiation and reflection.

The five parameter model is commonly used by standard simulation environments such as matlab, openModellica or HYDROGEM. In those environments it can be easily coupled to power converters, control algorithms, or larger integrated systems.

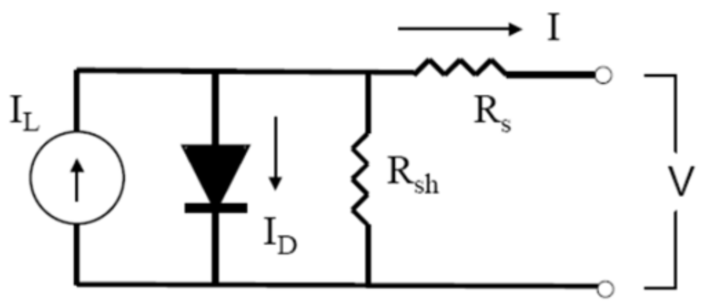

Figure 5: open circuit model of a photovoltaic array (Ete, 2009)

- **View Factor Model [Bifacial Photovoltaic]** (Asgharzadeh Shishavan, 2019), (Wang et al., 2015), (Hansen et al., 2017), (Pelaez et al., 2019): Bifacial photovoltaic systems need to be treated differently than regular PV systems as a solar yield can occur from both sides of the PV panel. While already existing models for front side irradiance are employed, the simulation of the back side irradiance calls for new models.

  In order to apprehend the full backside irradiance of the PV, view factors are calculated. The view factor is the fraction of the radiation from the front side surface that hits the backside surface. The view factor can be determined by assuming that all reflecting surfaces were Lambertian, i.e., irradiance was scattered isotropically. Alternatively, a ray tracing tool called Radiance can be used to simulate a forward and backward ray tracing and thus calculate the view factors.

  Modelling bifacial photovoltaic arrays additionally calls for an irradiance model, which calculates the solar position, projects the global radiation from the horizontal plane to the given orientation and tilt of the PV system, and separates the global radiation into direct, diffusive and reflective proportions.

- **Quadratic Efficiency Model [Solar Collector]** (Hernandez-Albaladejo and Urquia, 2018): The most popular model, which describes the behaviour of solar collectors is a steady state model. It is identified by an empirical, quadratic, efficiency law, which originates from theoretical equations developed by (Duffie and Beckman, 2013). The law accounts for the heat losses due to reflexion, absorption, heat transfer and convection. The empirical law contains three parameters, which are always provided by manufacturers. The heat losses are related to the square of the temperature difference of the collector and the ambient temperature, the linear difference, and the global radiation.

For the determination of the power of the system, calculations of the solar position are necessary to project the global radiation on a horizontal plane to the yield on the collector with given tilt and given orientation. Various methods exist to separate direct radiation from diffuse radiation and reflection.

The model does not account for dynamic and microscopic effects in the solar collector. Still, it represents the behaviour in the solar collector sufficiently well, and has a good computational performance. Implementations of solar collectors in libraries from TranSys, Modelica or Soltermica are commonly based on the description above.

- **Hybrid Models - TranSys [Photovoltaic] [Solar Collector]** (Jonas et al., 2019)**:** Hybrid models have the dual purpose of creating power from embedded photovoltaic (PV) cells and providing heat.

  One hybrid form consists in heating an air stream passing beneath the absorbing PV surface. The model then needs to operate with simple building models that can provide the temperature of the zone air on the back-side of the collector and possibly provide an estimate of the radiant temperature for back-side radiation calculations (the room air temperature may be used as a suitable estimate of the radiant temperature if surface temperatures are not available).

  Another known hybrid form is the so-called PVT (photovoltaic thermal), which couples a photovoltaic array with a solar collector. For the thermal performance model, a two-node model is applied. It adds a functionality of electrical performance to the thermal model of a solar collector. A combined identification of thermal and electrical model parameters is the most suitable approach regarding accuracy and processing effort.

- **Models for Combustion Engines [Combined Heat & Power]** (Abunku and Melis, 2015), (Sun et al., 2018), (Borelli et al., 2015): In general, a combined heat and power unit consists of an Internal Combustion Engine (ICE), and two heat exchangers: One heat exchanger picks up the heat flow from the refrigerant and another one from the flow of exhaust gases, which have very high temperatures.

  The behaviour of the ICE can be described using a characteristic curve based on the percentage load. The performance curve of the ICE describes the value of the heat flow and electric power generated for each load value of the machine.

  Alternatively, a detailed formulation for the ICE, which involves the analysis of the real thermodynamic cycle and requires the modelling of the engine and the real combustion process, can be undertaken. For example Simulink/Matlab provides the necessary components for such a detailed analysis. The resulting model is accurate and slow in computation.

- **Detailed Model for Fuel Cells [Combined Heat & Power]** (Cheddie and Munroe, 2006)**:** A fuel cell is a combined heat and power unit, which converts hydrogen to electrical energy producing excess heat. The processes within a fuel cell are well described by CFD. In detail, the continuity equation, the Navier Stokes equation, the Stefan Maxwell Equation, Conservation of Mass, Charge and Energy, and the Butler Volmer equation form a closed set of coupled partial differential equations, which mathematically express the dynamics within a fuel cell. All compounds are assumed to obey the ideal gas equation and to be in the gaseous phase. The system can be discretized and solved by a finite element method. The model allows a detailed analysis of microscopic processes in the fuel cell, but has the drawback of high computational costs.
- **Generic Model for Fuel Cells [Combined Heat & Power]** (Njoya et al., 2009), (Deseure, 2020), (Kim et al., 2010)**:** This model represents a simple and efficient method to characterize and predict behaviours of fuel cell modules. The state of the system is simply defined by the temperature of the stack, the load current, and the output voltage. The output voltage is related to the load current by an empirical law, which includes the Nernst potential as well as the activation, ohmic and concentration overpotentials. Those potentials are defined by other empirical laws, which need the stack temperature and the partial pressure of hydrogen and oxygen as input. The stack temperature is approximated by another empirical law, which relates it with time. Obviously, the generic model is computationally less intensive. The difficulty in its application is the definition of all necessary parameters from the manufacturer's datasheet or by measured data.
- **Turbine with fixed rotational speed [Wind Power]**[57, 58]: The model is based on the assumption that the wind turbine rotates with a constant angular velocity. Then, the efficiency curve of the turbine can be expressed as a function of the wind velocity. Under normal conditions, wind speed data is spikey. Therefore, estimations of the energy produced by a wind turbine improve, when using distributions of wind velocities instead of average wind speed data. Wind speed distributions show Weibull Characteristics. The power of the wind turbine can be calculated by the integral of the product of the efficiency curve and the wind distribution over the wind speed range.
- **Turbine with variable rotational speed [Wind Power]** (Eberhart et al., 2015), (Ben Ali et al., 2017, (Modukpe and Dei, 2020)): The model is intended to study the dynamic behaviour of wind turbines with variable wind speed. The formula for the kinetic energy of wind in combination with an empirical formula for the wind turbine function based on 6 turbine specific factors, the internal wind tip ratio and the pitch angle describe the mechanical behaviour of the wind turbine. The turbine coefficients reflect the actual geometry of the wind blades. Both uncontrolled and controlled wind turbines can be simulated that way.

  In addition, the mechanical model is coupled to a generator and grid components, to accurately model the electricity production. A detailed model, which considers almost every element of the wind turbine (wind source, turbine, pitch- and torque

[57] https://de.mathworks.com/products/demos/symbolictlbx/wind-turbine-power.html
[58] http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/pwr.htm

control, inverters, etc.) can be seen in Figure 6. As the model is quite detailed, the time resolution is lower. For that reason the model works with both, average data or distributions of wind speed.

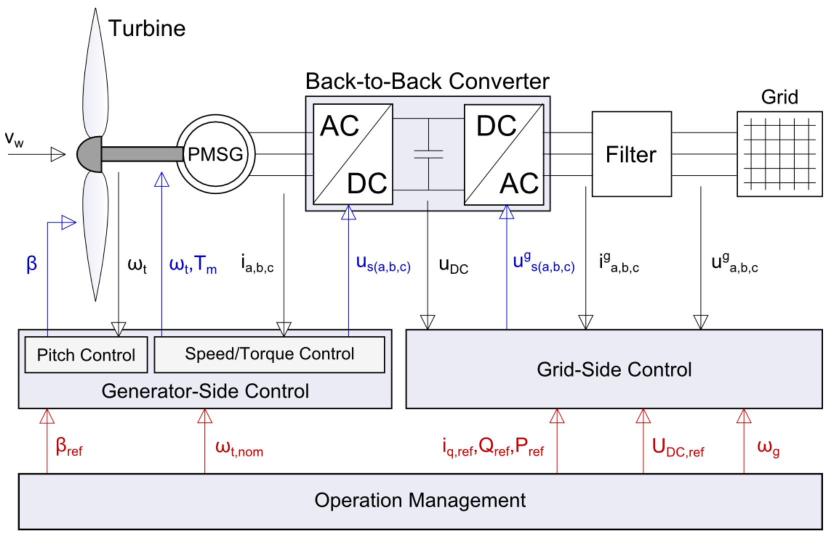

Figure 6: Detailed Model of a wind turbine[59]

4.11. Modelling business models in the field of electrical consumption on household level

This chapter sets the focus on business models or options to interact with the energy system which are available to energy consumers on household level. Until recently, household energy consumers played a very passive role in the energy system, being reduced to only consuming energy and paying for the energy consumed. With the energy system and the energy markets opening up in all EU Member States, due to new laws and regulations (e.g. Energy Union) and the technological developments in decentralised generation technologies and controllable flexible loads (storages, heat pumps, etc.) formerly passive consumers are getting more attention and are obtaining more active roles in the EU energy markets. Also due to technological advancements, service providers have developed new services (specifically) for households.

To create profit from these new possibilities, new business models have been developed, which are offered to household consumers to gain more out of their assets or reward certain behaviour. These new business models are relevant to WHY as they affect the behaviour of the consumers and will also influence their decision on how to invest or not invest in new low-carbon technologies in the future.

The term business model in the context of Deliverable D1.2 is very broad, as it describes an opportunity for household energy consumers to partake in the energy system and energy markets and use their assets for an economic and/or ecological profit or become

[59] https://www.claytex.com/products/dymola/model-libraries/wind-power-library/#1499026147166-3b703c57-87b4

customers of new services. The next sections provide an overview of the Business Models relevant to the WHY project.

4.11.1. Energy as a Service (EaaS)

The EaaS is an innovative model whereby a service provider offers various energy-related services rather than only supplying electricity. Energy Service Providers (ESP) can provide:

- **Energy Consulting** which aims at helping customers benchmark their costs against the market for optimising energy consumption thus resulting in a reduction of costs for energy consumption.
- **Finance schemes for Assets:** Energy service providers can facilitate access to finance new assets, such as decentralized renewable energy sources or energy storage systems. Money can be reimbursed for instance through monthly fees.
- Provide the consumers with **Energy management (technologies)** to monitor energy consumption or remotely control loads to optimise own consumption rates or reduce peak loads.
- **Energy tariff changes** have become possible due to the Electricity Market directive, allowing customers to choose their energy provider on the basis of tariffs rather than their location. Energy service providers offer the service of screening possible tariffs for customers and handling the administrative work of a change of the supplier. As reimbursement a part of the cost saved through the tariff change will stay with the service provider.

4.11.2. Peer-to-peer electricity trading (P2P)

Peer-to-peer electricity trading is a very novel concept in the electricity system as it allows consumers to exchange electricity (surplus of one's own generation) without an intermediary (energy supplier). Different options for realising P2P trading are available, such as direct power purchase agreements or the use of an interconnected web-based platform. The latter serves as an online marketplace where consumers and producers meet to trade electricity directly, without the need for an intermediary, just like an open market economy.

The electricity is transacted between users that become members of the platform, for example by paying a monthly subscription fee. This model can be established among neighbours within a local community, as well as on a larger scale, among various communities. The P2P platform is able to operate between subscribers that are part of the main distribution system or that are part of an isolated mini-grid.

This business model can, as of April 2021, not be implemented in every member state in Europe as the energy laws and regulations do not allow for P2P-Trade to happen. But with the Electricity Market Directive 2019/944 and the Renewable Energies Directive 2018/2001 member states are forced to introduce P2P and direct electricity selling of end consumers in the respective laws and regulations. For that purpose two new market roles, the active customer and the renewables self-consumer are being implemented.

4.11.3. Aggregators

An aggregator is a service provider that represents a group of agents (consumers, producers, prosumers, etc.) in order for them to act as a single entity in order to reach the thresholds required to enter certain market segments of the power system. Similar to the new market roles described above, aggregators are also defined in the Directive 2019(944 as a new market role. Aggregators are already active in multiple EU-member states providing their agents entry into market segments such as the wholesale electricity market, primary, secondary and tertiary power control, etc. As a reimbursement for their service, aggregators get a share of the profit of their agents.

Aggregators often work with so-called virtual power plants (VPP), which is an aggregation of dispersed energy sources, flexibilities etc. Through the VPP these assets can be monitored and controlled. The VPP is controlled by a central information technology where all data (weather forecast, electricity prices, power supply and consumption trends) is processed to optimise the use of the assets according to the strategy of the aggregator.

4.11.4. Community-ownership models

This business model aims at all sorts of collective ownership, management and use of generation capacities or energy related assets such as collectively used battery storage systems, etc. These models reduce the market and non-market barriers for individuals to invest money in renewable energy technologies and allows them to own (parts of) assets with lower levels of investments. There are different flavors of community-ownership models currently available and in development:

- **Community-owned assets focused on sharing the economic benefits:**
  The models aim at gathering a group of individuals to invest into an asset (currently mostly a renewable generation source). The asset is operated and maintained by a third party, often a municipality or an energy cooperative. The investors profit from the generation and sales of the energy and get certain interests on their investment.
- **Collective self-consumption schemes:**
  Rather than benefiting from income generated through selling energy from a shared asset, this model (which is not possible in all EU-member states at the moment) aims at providing the investors with the possibility to directly consume the energy generated by the collectively owned generation capacity. Depending on the local regulation up to the entire grid fees and large parts of taxes can be saved on the energy used directly.
- **Energy Community Models:**
  Advancing the self-consumption scheme, the energy community (renewable or citizen) allows its members to share electricity amongst one another. While collective self-consumption centres around one commonly owned or operated generation capacity, energy communities share multiple assets (also storage systems) in one community. The extent of financial benefits of using the energy provided by the community depend on the legislation and regulation of the corresponding EU-member state.

These Community-ownership models can be organised in multiple different ways, allowing them to be organised in a way that best suits the requirements and offers of the community. Below is an exemplary list of different types of organisation models.

- **Co-operatives**, which are jointly owned by their members. Decision making happens by votes, where one member gets one vote. Rely largely on volunteers but can have paid staff.
- In **Partnerships** the involved individual partners own shares of the community. They may employ staff to provide expertise needed.
- The organisation can be a **non-profit organisation** if it generates profits that are not distributed but rather re-invested in projects of relevance for the organisation.
- **Community trusts** are another option where reinvestment is of importance albeit it being used for a specific local purpose. These benefits are also shared with people who are not able to invest directly.

4.11.5. Pay-as-you-go Model

Pay-as-you-go-Models (PAYG) are a new approach at tackling energy poverty. There are different approaches to the PAYG model depending on whether the customers are situated in well connected regions or in remote regions with no or hardly any access to electricity.

While conventional energy supply models in regions where electricity is supplied via the public grid require a payment “at the end of the month/year” over the consumed electricity, PAYG requires the customers to pay up front. This gives them more control over their electricity bill and a better feeling for their energy consumption in general.

Furthermore PAYG can be used in regions that do not have a strong grid connection or regions where there normally would be no access to electricity due to a missing connection to the main grid. This model combines decentralised and isolated energy generation from renewable energy sources with the PAYG mode. Payment will be made in advance, enabling the users to receive electricity and slowly obtain ownership over the devices over micro payments. Thus enabling electrification of regions that otherwise would not have access to electricity.

These models can be implemented at the individual household level and at the broader community or neighbourhood level.

4.11.6. Conventional Energy Supply Models

These models, although the details will differ largely by country and individual energy supplier, are based on periodically measured consumption values over a certain amount of time (monthly, annually). Generally these models contain three elements:

- **Energy consumption related values** (cents/kWh): The “energy tariff” can either be a fixed value or a variable tariff, depending for instance on the time, the energy is consumed (given that there is a smart meter installed).

- **Power related values** (cents/kW): These costs (“capacity tariffs”) are related to the maximal power fixed by the contract or even on the measured values such as the annual peak load.
- **Fixed costs** (€): Energy bills can contain components that are not really influenced by energy consumption or power used.

Furthermore costs for energy supply can be separated in:

- **Energy tariff**: The tariff for the energy consumed and supplied by the energy provider.
- **Grid tariff**: This part of the tariff is used to finance the existing grid and the connection to the grid by the individual user.
- **Taxes and fees**: This part of the energy bill is very much dependent on the corresponding country but can make up a substantial part of the energy bill.

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