SOFTWARE TOOLS FOR LOCAL ENERGY SYSTEM OPERATION AND EXPANSION

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Software tools for local energy system operation and expansion

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Preface

Acknowledgements

The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities

The ZEN Research Centre develops solutions for future buildings and neighbourhoods with no greenhouse gas emissions and thereby contributes to a low carbon society.

Researchers, municipalities, industry and governmental organizations work together in the ZEN Research Centre in order to plan, develop and run neighbourhoods with zero greenhouse gas emissions. The ZEN Centre has nine pilot projects spread over all of Norway that encompass an area of more than 1 million m2 and more than 30 000 inhabitants in total.

In order to achieve its high ambitions, the Centre will, together with its partners:
- Develop neighbourhood design and planning instruments while integrating science-based knowledge on greenhouse gas emissions;
- Create new business models, roles, and services that address the lack of flexibility towards markets and catalyze the development of innovations for a broader public use; This includes studies of political instruments and market design;
- Create cost effective and resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies;
- Develop technologies and solutions for the design and operation of energy flexible neighbourhoods;
- Develop a decision-support tool for optimizing local energy systems and their interaction with the larger system;
- Create and manage a series of neighbourhood-scale living labs, which will act as innovation hubs and a testing ground for the solutions developed in the ZEN Research Centre. The pilot projects are Furuset in Oslo, Fornebu in Bærum, Sluppen and Campus NTNU in Trondheim, an NRK-site in Steinkjer, Ydalir in Elverum, Campus Evenstad, NyBy Bodø, and Zero Village Bergen.

The ZEN Research Centre will last eight years (2017-2024), and the budget is approximately NOK 380 million, funded by the Research Council of Norway, the research partners NTNU and SINTEF, and the user partners from the private and public sector. The Norwegian University of Science and Technology (NTNU) is the host and leads the Centre together with SINTEF.

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f   FME ZEN (page)

Abstract

This report describes existing software tools for analysing operation and expansion of local energy systems and is written in WP5 in the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN). WP5 in FME ZEN aims to develop and apply methodologies that identify the socio-economic optimal operation and expansion of energy systems within demarked areas. The eTransport model is planned to be further developed and used to analyse pilot cases in ZEN. This report provides a brief description of the eTransport model and other alternative models found in the literature or used by partners in FME ZEN. The models are assessed based on their suitability to address the planned research tasks in FEM ZEN WP5. The report also includes a description of models developed for global and international analysis.

Contents

1 Introduction

This report describes existing software tools for analysing operation and expansion of local energy systems and is written in WP5 in the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN). WP5 in FME ZEN aims to develop and apply methodologies that identify the socio-economic optimal operation and expansion of energy systems within demarked areas. In WP5, eTransport, which is SINTEFs existing software tool for local energy system optimization, will be further developed and improved. Other existing software tools could also be suited for the work planned in WP5. Other tools have therefore been identified and assessed according to their suitability for analysing the research questions in WP5, and are described in this report.

In Chapter 2, some of the research questions to be to be addressed in FME ZEN are described together with the needed properties for the type of models that are needed to address those research questions. Chapter 3 describes different models for energy system analysis that could be relevant for ZEN WP5. Chapter 3 is organized in three subchapters:

- eTransport
- Models used by ZEN partners
- Alternative models described in the literature

Chapter 4 is an overview of models that are applicable for studies with a wider geographical scope. Chapter 5 is a summary and discussion based on their relevance for the work planned regarding energy systems analysis in ZEN.

In most cases the tools considered in this report are so-called white-box models, and they are typically using a fixed consumption profile. Planning tools for the future energy system should also be able to consider new possibilities especially for demand response and storage. This will be important topics for the further developments carried out within FME ZEN.

2   Research questions and model requirements

2.1   Research questions and model requirements for WP5

The goal of ZEN is to enable the transition to a low carbon society by developing sustainable neighbourhoods with zero greenhouse gas emission. To achieve this, improving energy efficiency and flexibility of the building stock and integration of renewable distributed energy production and storage are important factors. When considering local solutions for serving energy needs, including local production, conversion between energy carriers, storage and infrastructure for energy transport, the full advantage of synergies with the surrounding energy system must be realized. In order to analyse operation and expansion of local energy systems with multiple energy carriers within a larger system, there is a need for detailed models.

Modelling of local energy system with multiple energy carriers can be divided into three phases. The first phase is to establish a future scenario, or a range of future scenarios. In the scenario phase, high-level technical design of the future energy system is established considering future goals and requirements for e.g. greenhouse gas emissions, renewable energy production, and energy efficiency. This includes to identify changes in the energy consumption, and which supply and storage technologies are required. The next step is to assess the operational feasibility of the scenarios. This includes to investigate the energy balance of the system through the year. The operational phase requires a relatively small timestep to account for different seasons and rapid variations in loads and generation. This phase could also provide feedback to the scenario phase to adjust the scenarios. Finally, the planning phase can assess how to get to the desired scenario. In this phase the optimal design of the future energy system and optimal investment plan, i.e. when to invest in certain technologies, is assessed. In this phase time steps of one to five years are normal when considering investments while the operational costs are determined using a smaller timestep, e.g. one hour. The planning phase could also provide feedback to the operation phase to check the feasibility of the system. All these phases are relevant for the work proposed in ZEN WP5.

For the work proposed in WP5 in FME ZEN, models designed to analyze local energy systems are needed. Local energy system models usually have more detailed modelling of technology like generation, storage and infrastructure than models designed for analyzing larger geographical areas. The models should be able to assess energy systems with multiple energy carriers and the interaction between the energy carriers. When considering Norwegian local energy systems, electricity and district heating is especially important, and the models should at least be able to represent these two energy carriers. Development of new models and methodology is a large part of the proposed work in WP5 in FME ZEN. Availability and possibilities for further development of the models in ZEN is therefore an important aspect, both to be able to include possible new innovations and to have control over the assumptions and simplification in the model. The models should also be able to consider greenhouse gas emissions. This includes the effect operation and expansion of local energy systems have on greenhouse gas emission and how different incentive systems for environmental friendly technologies affect the energy system. Possibilities to define KPIs and constraints related to energy use and greenhouse gas emissions are therefore important. The models should be able to assess both new energy systems, and development of ZEN in existing systems.

2.2   Related research questions in WP2

In WP2 of FME ZEN, the transition towards ZEN will be analysed from an international perspective in order to investigate the interaction between ZENs and the larger system. With an international perspective, models that support planning and operation of ZEN could highlight the international consequences of local investments, and the opportunities this creates beyond the neighbourhood. To investigate these aspects, models with a large geographical scope (national, international or global) are useful.

The purpose of models with a top-down perspective on an international or global level is to identify the benefit of linking regions together in an energy system and understand the changes and consequences that new developments bring about from a macro perspective. The top-down models can analyse the synergies between regions by capturing trading and economic aspects, but they are limited to represent aggregated and simplified elements of technical and regional components.

3   Models for local optimal planning and operation

3.1   eTransport

This chapter gives a brief description of the eTransport model developed by SINTEF Energy Research. For a detailed description of the model, please see [1, 2].

eTransport is an optimization model developed for expansion planning in energy systems, where several alternative energy carriers and technologies are considered simultaneously. The model minimizes total energy system cost of meeting a predefined energy demand of e.g. electricity, heating, and cooling within a geographical area over a given planning horizon. The model considers investment, operating, and environmental costs over a planning horizon of several decades, and can represent most relevant energy carriers and conversion between them. The model has functionalities to represent both continuous energy transport, such as lines, cables, and pipelines, and discrete transport, such asships, road or rail.

eTransport is separated into an operation planning module (energy system module) and an expansion planning module (investment module). The operation planning module finds the cost-minimizing operation for a given infrastructure and given energy loads, while the expansion planning module finds the optimal investment plan. Figure 1 shows an overview of the model.
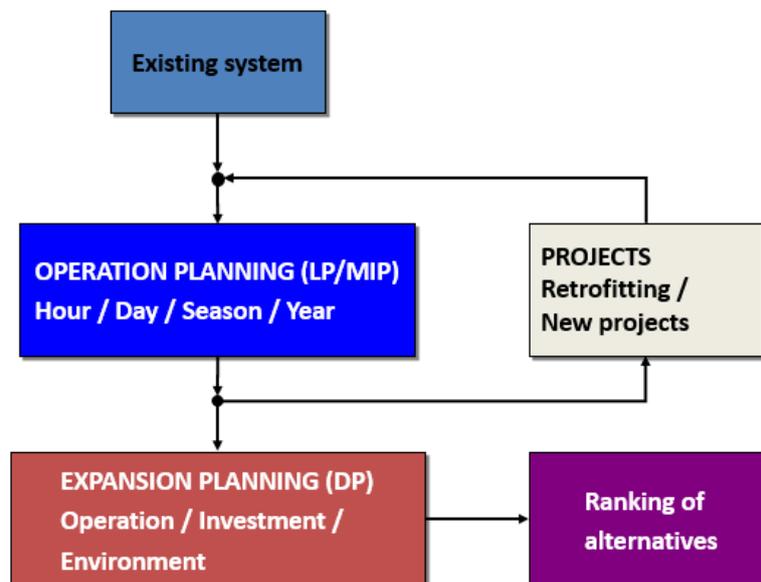
Figure 1: Overview of the eTransport model.[1]

The user creates a model of the energy system including energy producing units, loads, units for conversion between energy carriers, energy storage units, infrastructure for energy transportation, and connection to surrounding energy systems. The user also defines a set of investment alternatives, where each alternative may consist of several components and connections to the existing energy

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[1] LP, MIP, and DP stand for linear programming, mixed integer programming, and dynamic programming respectively.

system. Alternatives may also include scrapping of existing components. eTransport works through a graphical user interface with drag-and-drop functionalities, developed in MS Visio, while all data are stored in an Access database.

Operation planning module

The operation planning module finds the operation of a given energy system that minimizes the costs of supplying a predefined energy demand at different locations within the studied area. The system boundaries are implicitly defined by import and export of energy to the modelled system. The operation planning module includes sub-modules for each energy carrier and conversion components.

Season variation in loads, capacities, and prices are modelled by splitting the year into different seasons with hourly profiles. This is illustrated in Figure 2. The annual operation costs for different energy system designs are found by running the operation planning module for all different seasons, and different investment periods, for all relevant system designs.
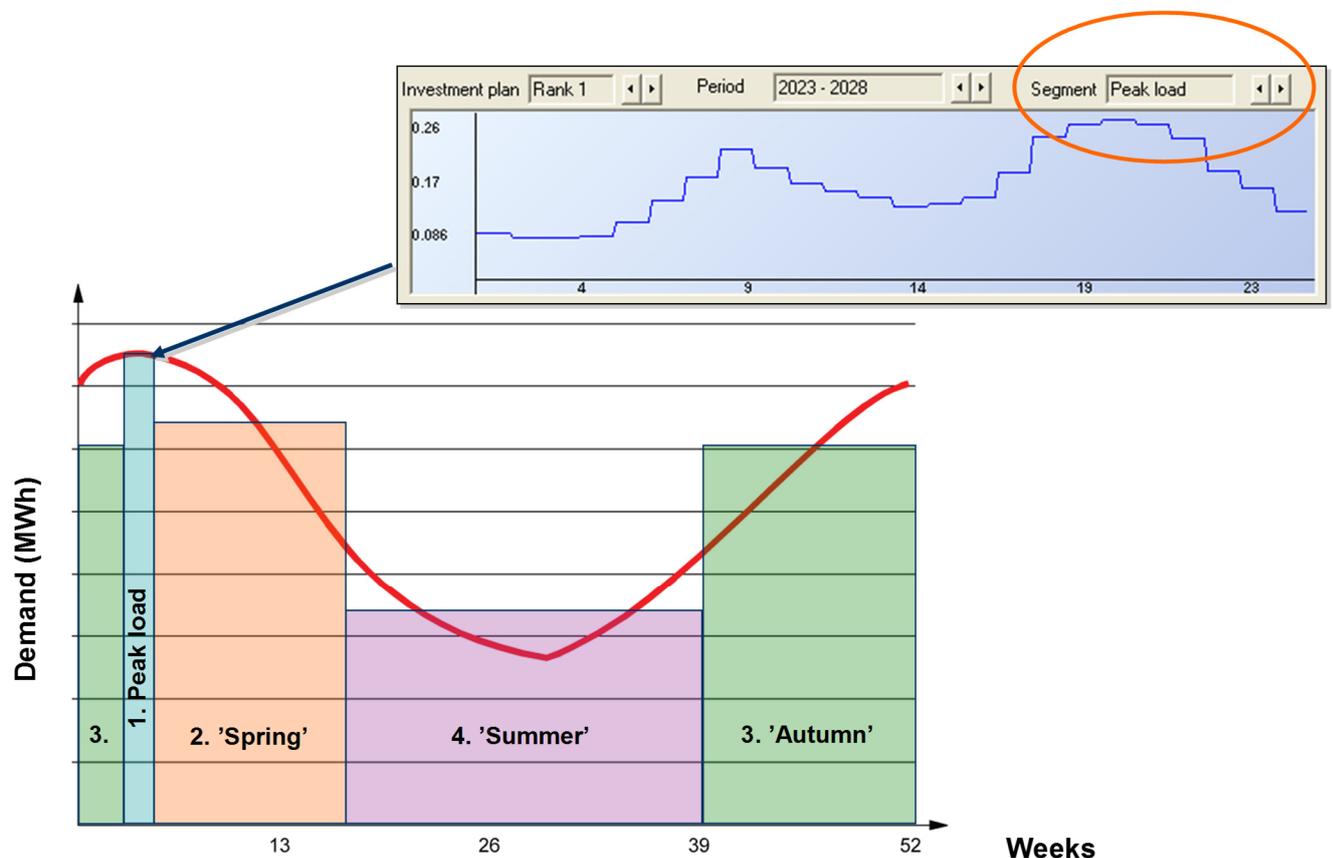
Figure 2: Annual load is split into seasons (lower panel), whereas each season is represented by a typical day representative day with hourly time-steps (upper panel).

The operation planning module is implemented in the AMPL (a mathematical programming language). A modular design, and functionality for easy connection to the database and the user interface, ensures that new technology modules are easy to integrate in the model.

Expansion planning module

The expansion planning module uses the annual operation cost calculated by the operation planning module to find the investment plan that minimizes the present value of all costs over the planning

horizon. The model also shows the ranking of the other expansion alternatives. The model will find the optimal combinations of investment alternatives including when the investments should be done, e.g. in what investment period. This is illustrated in Figure 3, where states represent different combinations of investment alternatives.
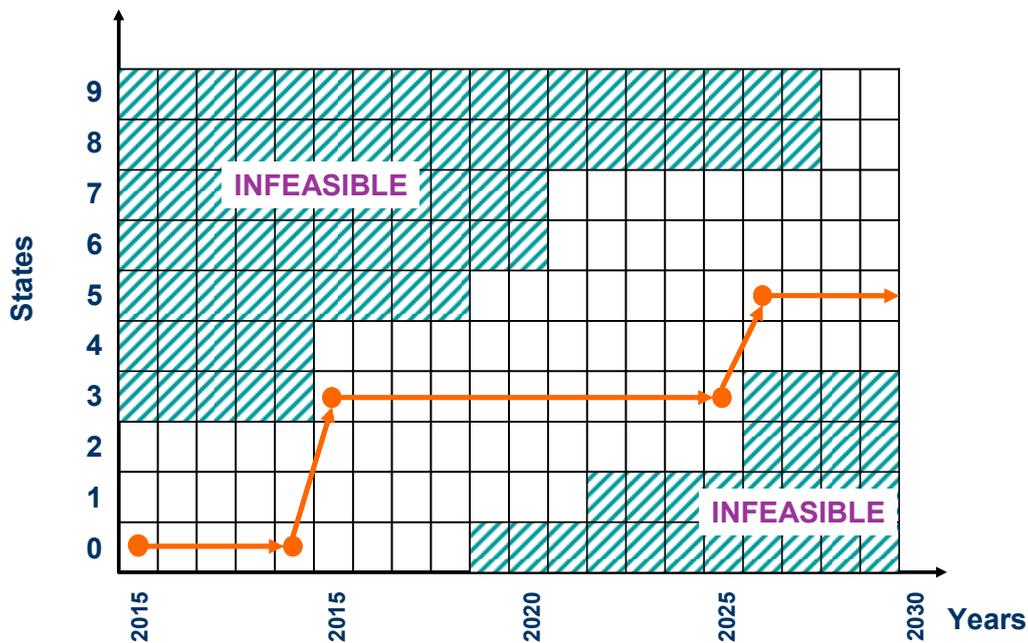
Figure 3: Optimal expansion plan.

As an addition to the classic eTransport model which uses deterministic parameters, a module is implemented for stochastic optimization. This module makes it possible to include stochastic variables by defining different scenarios for each investment period.

3.2   Models used by ZEN partners

This chapter describes models that are in use by the industry partners in ZEN for considering local energy system operation and control presented in a workshop arranged 2017-06-23 on Computer tools for planning of local energy systems. The chapter also describes models developed by ZEN research partners. The research partners in ZEN have been contacted in order to discover relevant models. In addition to these models, some research partners also use commercial software in their research. This includes the HOMER model, which is described in chapter 3.3.8.

3.2.1   TIMES

TIMES (The Integrated MARKAL-EFOM System) is a model generator for modelling of energy systems for the global, national, or even local scale. The user gives a description of the energy system including estimates of the energy demand, energy related equipment, characteristics of future technologies, and present and future energy sources and their potential. The model assumes perfect competition and perfect foresight and aims to supply energy services at minimum global cost by making decisions on equipment investment and operation of primary energy supply and energy trade.

The model is demand driven and investments are made to meet the future energy demand. It is usually applied to the analysis of the entire energy sector to explore possible energy futures, but may also be applied to study single sectors such as the electricity and district heat sector [3]. The TIMES model includes the entire process chain from primary resources, through transformation, transportation, and distribution, to consumption.

The TIMES model is developed as part of the IEA-ETSAP (Energy Technology System Analysis Program), and the source code is available for free. In addition to the model code, a data management system and a model solution is needed in order to run the model. The model is written in the programming language GAMS and requires a solver such as XPRESS or CPLEX. For handling input data and results, two data managements systems are available: ANSWER and VEDA. GAMS with solvers and the data management systems require licences.

There are several models built using the TIMES model generator. In the following, the functionalities of TIMES will be described by describing the TIMES-Norway model, which is a TIMES model with a more detailed description of the Norwegian energy system.

TIMES-Norway
TIMES-Norway is developed by the Institute for Energy Technology (IFE) on commission of The Norwegian Water Resources and Energy Directorate (NVE), and is a TIMES model with a description of the Norwegian energy system. The model is in use in several research projects and is continually updated. Typically, the model has been used to analyse a number of different aspects of the energy system, including the effect of different incentives to increase electricity production from renewable sources, and different demand scenarios.

The TIMES-Norway model uses a time resolution where five time slices are defined for each week, giving in total 260 annual time slices. The model divides the energy system into 7 geographic regions which are more or less unions of the 18 Norwegian counties. The model can therefore to some extent represent bottlenecks in the Norwegian energy system.

Energy resources and conversion / processes
The model includes current production, and renewable and fossil energy resources in Norway, their associated cost, and potential for different energy carries. The TIMES-Norway model includes several different energy resources and production processes. Both reservoir and run-of-river hydro power plant are included. Hydro power plants with reservoir are modelled by weekly inflow series, where the water can be stored or used directly to produce electricity. Run-of-river hydro power plants are modelled with a load curve (i.e. hydro inflow), and wind power are modelled with wind profiles. Import of different energy carriers are also included in the model.

The TIMES-Norway model includes several models for generation and conversion between energy carriers, including electricity production, heat production, bio mass processing, and hydrogen production.

Transmission / distribution

The electricity transmission system is modelled by a high voltage electricity system and a low voltage electricity system. Electricity are generated by various power plants and fed into the high voltage grid within each region. High voltage electricity can either be used directly (typically in different industry processes), exported, transferred to another region or transformed into low voltage electricity. Similarly, a low voltage electricity grid exists within each region. Electric losses are considered by a fixed factor of 3 % for the high voltage network and 7 % for the low voltage network. Connections between each region and from regions to other countries are modelled by specifying an export/import capacity.

The use of district heating is currently limited to one grid per region. District heating grids are modelled by specifying a capacity and the losses of the heating is set to vary with each time slice.

Demand technologies

Energy loads are divided between electricity and heating, where heating include both space heating and hot water, and electricity is energy demand that cannot be replaced by another energy carrier. The TIMES-Norway model includes load profiles for electricity and heat demand for several different types of buildings within the residential sector, service sector, and industry sector. It also includes demand profiles for short distance personal cars, and constant loads for industry and the rest of the transportation sector. Energy demand forecasts for the different regions are also included in the model.

TIMES-Norway includes models of several so-called end-use-technologies, e.g. different technologies for both water-borne and direct heating systems like boilers and stoves. End-use-technologies are represented with a cost, lifetime, potential and capacity and any political restrictions in the use of the technologies.

Link with the EMPS model

TIMES-Norway was initially developed to be used together with EMPS (EFI's Multi-area Power-marked Simulator, NO: Samkjøringsmodellen, see Chapter 4.2.3). The models then communicate as follows: The EMPS model starts by supplying electricity prices from each of the regions in EMPS to TIMES-Norway. Based on this, the electricity consumption is determined in TIMES-Norway. This consumption is then input to EMPS. The iteration procedure will continue as long as there are significant changes in either electricity prices or electricity consumption from one iteration to the next. The TIMES-Norway model can also be run separately.

TIMES-Oslo

A TIMES model representing the energy system in Oslo has been developed by IFE. The purpose of this model was to analyse how Oslo can reduce its greenhouse gas emissions by 2030 and 2050. The model has been used to analyse the effect of different measures aiming to help Oslo reach their ambitious climate goals.

TIMES-North Europe

TIMES-North Europe is a TIMES model that covers the energy system in Denmark, Norway, and Sweden, and the electricity sector of Finland, Germany, the Netherlands, and the UK. The model was developed by IFE in cooperation with NTNU.

TIMES has been used by ZEN partners to investigate the impact of a large introduction of Zero Emission Buildings (ZEBs) on the Scandinavian energy system [4]. This analysis mainly identifies consequences of decreased demand and increased local PV production on the energy system. Local storage is not included.

3.2.2   Klimagassregnskap.no

Klimagassregnskap.no is a web-based model for calculating greenhouse gas emissions for buildings and construction projects. The calculations include all greenhouse gas emissions related to all activities and production factors associated with building, operation and maintenance, and transport of the building users, regardless of where the emissions are produced. The model calculates the buildings' total greenhouse gas emissions in CO2 equivalents and can be used for both new buildings and existing buildings. Development of the model is financed by Statsbygg, and the model is available online and free to use.

Statsbygg has made an agreement with Bionova to deliver a new model based on the One Click LCA software that will replace klimagassregnskap.no.

The model is divided into one general module and separate modules for handling plot choice, outdoor areas, transport, energy use, materials, and construction.

In the general module, the user specifies the goal of the project, the main characteristics of the building and general project data, and the system boundaries. EPDs (Environmental Production Declaration) for different materials can be included in a register in the model. In the materials module, the material quantities can either be specified by the user, or calculated based on a few simple input parameters – this is typically used in early phase planning. Based on the material quantities and EPD, the emissions are determined. The plot choice module calculates greenhouse gas emissions due to changed use of area based on the existing soil conditions, buildings, and vegetations, and the planned use of the area including buildings, paved and unpaved areas, green areas etc. The outdoor area module calculates the emissions from creating and maintaining outdoor areas. The transportation module calculates the greenhouse gas emissions due to transportation of people and goods during the lifetime of the building based on the building's localisation and the employees' and visitors' means of transport. In the energy use module, the emissions are calculated based on the energy need for heating, cooling, and electricity specific energy need and the building's planned energy supply. The construction module calculates the emissions from transport, construction machinery, and stationary energy use during the construction of the building. The inputs to this module are description of the transport needs (number of rides and average distance for various vehicles, fuel used etc.), quantities of different fuels used by construction machinery, quantities of fuel or electricity used for stationary energy use.

3.2.3   Optimal energy system design for ZEB using MILP

Karen Byskov Lindberg has as part of her PhD thesis, financed through FME ZEB, developed a model for optimal energy system design of zero emissions/energy buildings (ZEB) using MILP [5-7]. The purpose of the model is to assess the optimal dimensioning of the energy technology system from the building owner's perspective. The model uses relatively detailed component models, and both

investment and operational costs are included. The model is implemented in the optimisation modelling tool MOSEL Xpress.

The energy technologies that are implemented in the model are:
- Micro combined heat and power
- Gas boiler
- District heat exchanger
- Bio pellets boiler
- Air source heat pump
- Ground source heat pump
- Electric top-up coil
- Solar thermal collectors
- Photovoltaic modules
- Heat storage

The electric top-up coil, the district heating, and the gas, and bio pellets boiler are modelled with a constant efficiency. The CHP is modelled with one efficiency for the heat generation and one for the electricity generation. The coefficient of performance of the heat pumps are represented by a polynomial to include the dependence of the supply and source temperature. The generation from the solar thermal collector and the solar cells are dependent on the total irradiation on the tilted plane which varies hourly. The efficiency of the solar thermal collectors is represented by a polynomial. The efficiency of the photovoltaic module is dependent on the cell temperature, irradiation, and the outdoor temperature. The heat storage is modelled as a single node serving both the hot water and the space heating demand, with a constant efficiency factor.

Important inputs to the model are energy and technology costs, hourly electricity and heat demand, taxes and feed-in tariffs, and weighting factors. Important outputs form the model are system costs, emissions, primary energy consumption, invested capacity and fuel consumption. The lifetime of the building is divided into periods, and the model is run for a representative year within each period with an hourly time resolution.

Hourly heat and electricity demand is given as input to the model, where the heat demand include both hot water and space heating, and the heat and electricity demand must be met every hour. The different technologies are specified with a cost and a minimum required capacity. The model also includes energy market conditions such as feed-in tariffs, investment subsidies, peak load tariffs or other grid tariffs, and it is possible to specify different tariffs on the different technologies (e.g. a lower tariff on electricity use by heat pumps compared to normal electric consumption). Different weighting factors, such as primary energy factors or carbon factors, related to how zero emission/energy buildings are defined, can also be specified.

The objective of the model is to minimize the discounted investment and operational cost. The investment problem and the operational problem are solved at the same time, and the least cost solution for operation of the building with the optimal technologies and their sizing is found.

The model has also been used to determine the grid impact of zero emission or zero energy buildings and to assess the effect different policy incentives has on the optimal ZEN energy system.

3.2.4   PI-SEC Indicator Tool [8]

The PI-SEC Indicator Tool is under development in the PI-SEC research project. PI-SEC aims to deliver efficient Planning Instruments for Smart Energy Communities. Within the project, a set of Key Performance Indicators (KPI) for SEC planning has been developed. Theses KPIs has been the basis for the PI-SEC Indicator Tool. The tool is an excel-based tool to help municipalities and other stakeholders understand how different development strategies influences chosen KPIs and targets. By the use of scenarios, the tool compares how the selected KPIs are influenced by strategic choices and ambition level. In this way the tool is helpful for setting realistic goals and targets, for linking specific measures and decisions to the neighbourhood performance, and for follow-up throughout the project.

The Indicator Tool does not perform detailed simulation, but compiles best knowledge (from measurements, simulations or normative numbers), to give an overview of the neighbourhood performance. Inputs to the tool are yearly energy and emission related data on the buildings within a neighbourhood (on individual building or aggregated level), energy related infrastructure (e.g. outdoor lighting and snow melting systems), local energy production (thermal and electric), district heating systems, and transport. Initially a description of the current situation is developed. Then a baseline development scenario is described, with new buildings and infrastructure and ambition level according to current building regulations (TEK). Based on this, new development scenarios with different strategies and measures can be developed and compared against the KPIs.

For **buildings**, the existing buildings are defined related to size, residents/employees, users, energy consumption, energy carriers and energy production. Buildings can be described individually, or as a group of buildings with the same properties. Energy consumption is split into purpose: heating, hot tap water production, cooling, and utility electricity consumption. For each of the thermal energy demands, energy source, production efficiency (COP) and distribution efficiency must be defined. If any renewable energy production systems, such as solar PV, are installed, these are described with area, peak power and yearly production. All energy related data should be normalized to a mean year. For **infrastructure**, the focus in the tool is on energy consuming infrastructure, such as street lighting and snow melting systems. Input data, such as estimated yearly energy consumption, must be supplied. For **local energy plants**, data on central units for energy production that are located inside the neighbourhood/area are added. This option is meant for production units that are connected to the district grid (thermal or electric). This could be units such as biofuel Combined Heat and Power systems, solar thermal or Photovoltaic (PV) parks. For each energy plant, the energy source, total efficiency, peak capacity and yearly production must be specified. Capacity and production data can be specified for heating, cooling and electricity (either on or a combination of the three). For **district heating**, the yearly average distribution between the energy sources used in the heat production must be defined. In this phase, the use of district heating will be calculated from the building and infrastructure data. The **transport** module is based on the number of residents, employees, and users for the individual buildings. This information is described in the building module. In the transport module, the data is summarized and distributed into building categories. In addition, data on traveling habits within the area must be supplied. This is information on number of travels generated by residents/employees/users, mobile splits, average travel distances and number of passengers. It is also possible to adjust a parking factor (0-1), that reduces the share of travels with private cars (if below 1), due to parking area availability [9]. This information is usually extracted from travel surveys.

CO2 emissions: Total tonnes
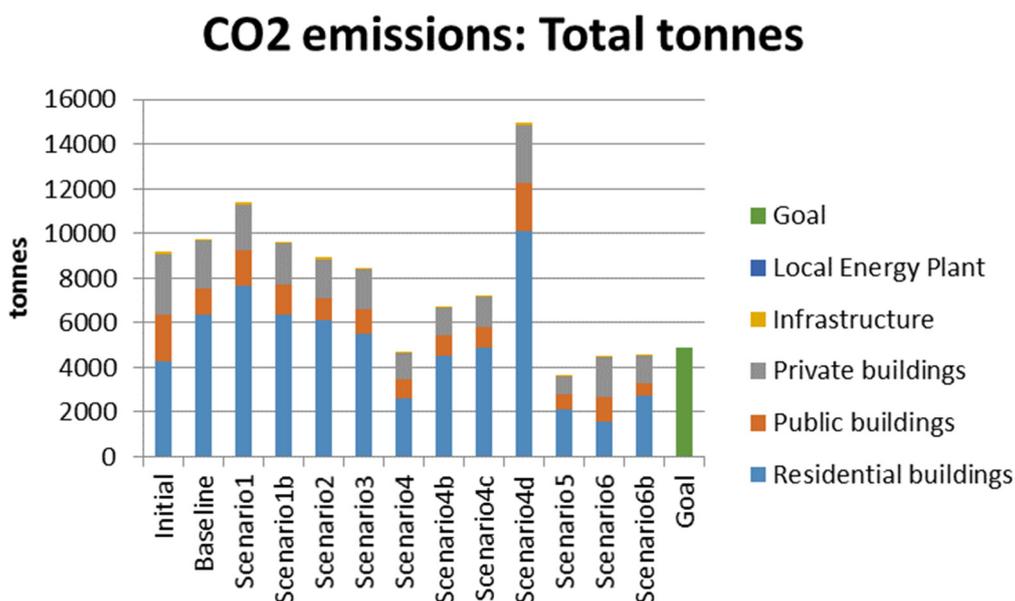
Figure 4: Example output from PI-SEC Indicator Tool. Total CO_2 emissions from stationary energy use within an area.

The tool is currently under development within the PI-SEC project and is being tested by both municipality planners and energy consultants. It is currently also being evaluated for use within the ENOVA "konseptutredning"[2] program and for developing energy strategies within BREEAM Communities[3].

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[2] https://www.enova.no/bedrift/bygg-og-eiendom/konseptutredning-for-innovative-energi--og-klimalosninger-i-bygg-omrader-og-energisystem/

[3] http://ngbc.no/breeam-nor/

3.2.5   Energy system analysis tool for early design phase of ZEB

The "Energy system analysis tool for early design phase of ZEB" was developed in the FME-ZEB research centre on zero emission buildings. It is an excel-based post-processing tool that receives input data from building performance simulation tools, such as IDA-ICE. The tool provides output KPIs (Key Performance Indicators), incl. cost optimality, and graphs that assist the design team making decisions in the early phase of a design process. Since it explicitly analyses the balance between energy use and onsite energy generation, it is especially suited for analysis of ZEBs.

This tool addresses in principle just single buildings, and guidelines on how to use it are available in [10]. However, the tool may be used also for analysis of clusters of buildings, provided that building performance simulations are performed for the required building typologies, as done in [11-13].
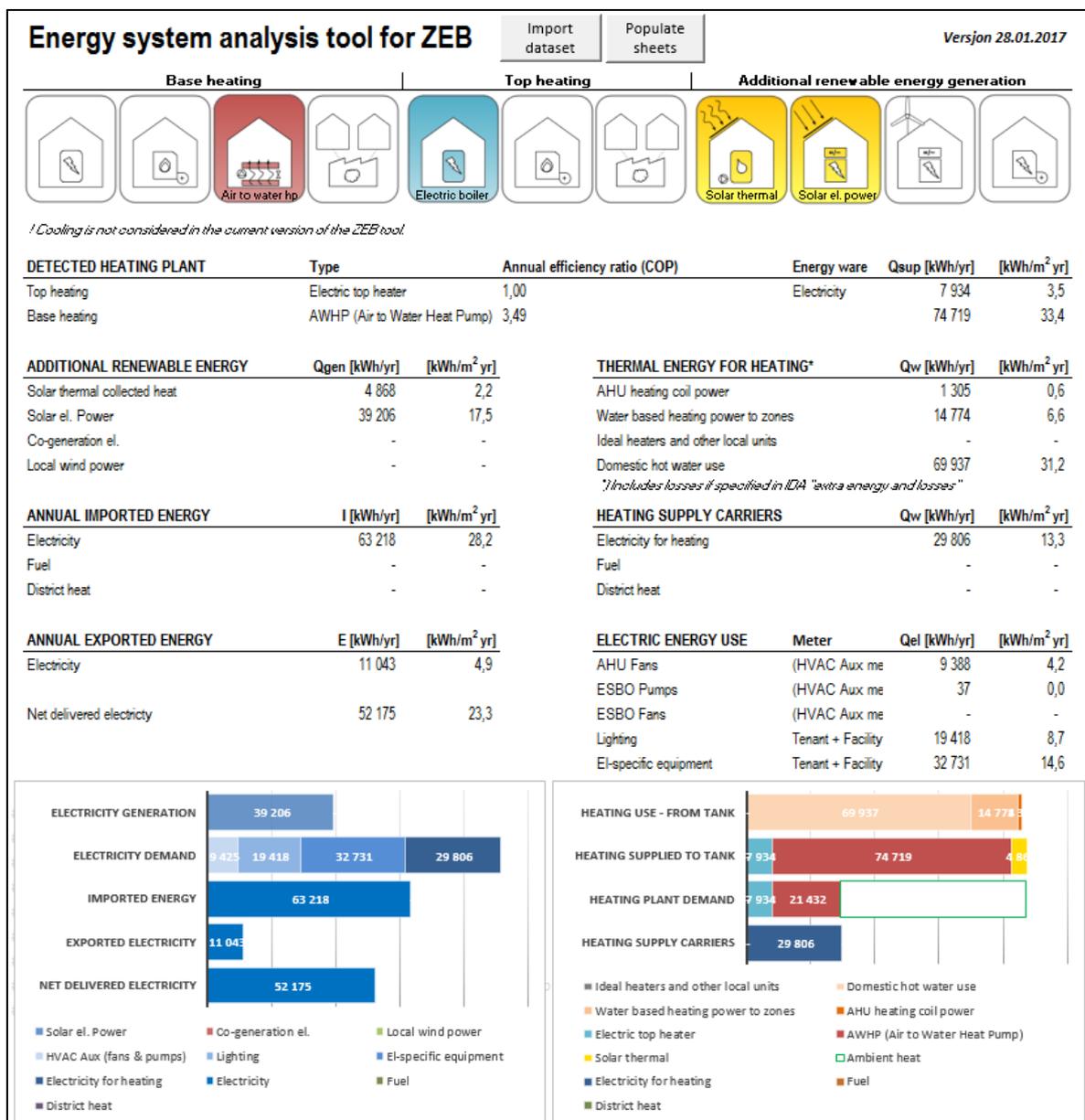
Figure 5: Summary sheet of the ZEB tool, outlining the main KPI of the energy system.

3.2.6   Aggregated load profiles: database predictor

This tool, developed in the FME-ZEN centre [14], could be described as a black-box model (purely statistical) since the only physical relationship it contains is a linear dependency between the overall thermal and electric energy needs of buildings and the outdoor temperature. The tool calculates the expected energy needs, split in thermal and electric, of a neighbourhood by aggregating the typical profiles of various building categories, weighted by their floor area. The temperature dependent typical profiles are obtained applying linear, on an hourly basis, regression coefficients that are specific for each building category (house, office, school, etc. and 'normal' or 'energy efficient'). Such coefficients are extrapolated by analysis of relatively large databases of well monitored buildings (dozens for each building type), with hourly resolution. The background work is anchored in [15] for the residential buildings and in [16] for the service buildings.

3.3   Alternative models – literature review

In this chapter, other software tools for local energy system operation and expansion found in the literature are described. The following review articles have been assessed in order to identify models and tools that can be used for analysing local energy system operation and expansion within a larger system[17-20]:

- P. Mancarella, "MES (multi-energy systems): An overview of concepts and evaluation models," 2014.
- J. Allegrini, et al., "A review of modelling approaches and tools for the simulation of district-scale energy systems," 2015.
- D. Connolly, et al., "A review of computer tools for analysing the integration of renewable energy into various energy systems," 2010.
- I. v. Beuzekom, et al., "A review of multi-energy system planning and optimization tools for sustainable urban development," 2015.

In addition, an overview of energy system analysis models available at www.energyplan.eu/othertools were also considered. These sources describe in total 62 models. To limit the number of tools, only the tools that meet the following criteria were assessed:

- Minimum hourly time resolution
- Applicable for local energy systems
- Possibility for analysing multiple energy carriers including at least electricity and district heating
- Include costs

In order to capture the effects of variations in load and generation, and the requirements this sets for the dimensioning of the system, only models with a minimum time resolution of one hour were considered.

Electricity and district heating are believed to be the most relevant energy carriers for pilots in FME ZEN. Thus, only tools able to represent multiple energy carriers, including electricity and district heating were considered. Only models applicable to local energy systems were considered. Some models normally applied in a slightly smaller or larger scale, e.g. models used for national energy system analysis, were also assessed, but international and global models were not considered. The

models should be able to study various costs associated with local energy systems, and the models should at least include operating expenses, and preferably also capital expenses.

This resulted in fifteen models including the previously described eTransport and TIMES models. The other thirteen models are described in the following.

3.3.1   Balmorel

Balmorel is a model with emphasis on electricity and combined heat and power sectors in an international perspective. The model was developed to analyse the electricity and combined heat and power sectors in the Baltic Sea Region, and the focus of the model was analysing relevant international policy questions. The model is constructed for analysis of long term perspectives of development of the energy sector of a large geographic area. The model is formulated in GAMS and is developed under open source ideals.

The model includes several generation technologies including hydro power with and without storage, wind power, PV, viz, condensing, back pressure, boilers, and heat pumps. The model will find the optimal investments regarding generation capabilities or electric transmissions capabilities. The time resolution is flexible, and the model splits a year into time slices to account for variations in demand and supply, when studying several years, or the year can be split into 8760 time slices when studying a shorter time span. Balmorel has a relatively simple model of electricity transmission and distribution networks and district heating networks.

3.3.2   COMPOSE

COMPOSE [13] (Compare Options for Sustainable Energy) is a tool for evaluation of user-defined sustainable energy projects in user-defined energy systems allowing for user-selected methodology options. COMPOSE assesses to which degree energy projects may support intermittency, while offering an evaluation of the distribution of costs and benefits under uncertainty. The model is developed as part of a PhD thesis at Aalborg University.

The model can simulate different energy carriers and different generation and storage units. COMPOSE allows for the evaluation of a project's relocation coefficient, economic cost-effectiveness of relocation, economic costs, as well as both local, avoided, and system-wide CO_2 emissions and consumption of primary energy resources. The model uses an hourly time step over a user defined analysing period.

COMPOSE interacts with several other models. COMPOSE imports annual and hourly profiles from Energinet.dk and RAMSES, and optionally also from EnergyPLAN, while projects, including the optimized hourly production profile for each production unit, are imported from energyPRO. Hourly profiles can also be generated based on climate data form RETScreen. It is free to download.

3.3.3   DER-CAM

DER-CAM (Distributed Energy Resources – Customer Adoption Model) is a physically-based optimization model. The model uses a mixed integer formulation, and the objective of DER-CAM is to minimize the cost of operating generation and combined heat and power systems at customer sites

or in microgrids. The model finds the cost-optimal configuration of distributed generation technologies and the appropriate installed capacity, and finally the optimal operation to minimize the cost of energy based on the load and price information. The DER-CAM model is developed and maintained by the Lawrence Berkeley Laboratory in USA, and the model is free of charge.

There are two different branches of the model: *Investment and planning*, and *Operations*. The investment and planning branch finds the optimal investment decisions in local generation and storage given loads, utility tariffs, weather resources and other constraints. This is done using representative day types, e.g. weekday, weekend, and peak load, that covers a typical year with an hourly time step. Once the capacity is known, the operation branch is used to optimise the operation of installed generation and storage. This is done on a week-ahead basis with a time step down to 1 minute. Energy loads are predicted based on weather forecast. The Operations DER-CAM can also be installed locally in a building or micro-grid and act as a supervisory controller.

The DER-CAM model considers electric loads, space heating, water heating, cooling and refrigeration loads, and specific natural gas loads. Several generation technologies are available in the model, including combustion engines, fuel cells, micro-turbines, CHP, photovoltaic panels, solar thermal collectors, and wind power generators. Energy storage technologies included in the model are electric batteries, both stationary and mobile in the form of electric car vehicles, and heating and cooling storage.

The latest version of DER-CAM also includes modelling of electrical and thermal networks. A linear power flow model including active and reactive power is used to model constraints and calculate the losses both in radial and meshed networks. A linear heat transfer model including losses are used for thermal systems.

The model includes different tariffing possibilities that allows complex energy and power charges, and the model is also capable of modelling different energy management strategies such as demand response, load shifting and load shedding. The latest version of DER-CAM also considers various ancillary service markets such as spinning and non-spinning reserves, and up and down frequency regulation. The model also considers investment in building shell improvement, such as windows or insulation, as alternative to generation and storage technologies.

The objective of the model is typically economic were decisions are compared to a base case scenario. It is also possible to consider an environmental objective function to find the solution that minimizes the total greenhouse gas emissions. A multi-objective function is also possible to find a trade-off between economic and environmental goals.

Key inputs to DER-CAM are:
- Load profiles at each node, disaggregated by fuel type and end-use
- Electricity and gas tariff rates
- Ancillary service market data
- DG parameters: capital, operation, and maintenance cost, rated power, and efficiency
- Electrical network parameters
- Thermal network parameters

- Operating reserve parameters
- Financial parameters and constraints

The main outputs of DER-CAM are:
- Optimal selection and capabilities of DER at each node
- Optimal scheduling strategy
- Several other detailed economic and emission results.

DER-CAM uses a user friendly graphical user interface, and the results are presented in an Excel spreadsheet and shows detailed costs for the optimal solution. A simplified web-based version is also available.

3.3.4   EnergyPLAN

EnergyPLAN is a tool for analysing energy, environmental, and economic impact of various energy strategies. The main purpose of the model is to assist in the design of national or regional energy planning strategies based on technical and economic analyses of different energy strategies and investments. However, the model has also been applied to the European level, as well as local levels such as towns or municipalities. The focus of the model is to analyse the interaction between electricity, gas, and district heating and cooling grids. The model analyses a variety of options which are compared to each other. EnergyPLAN optimizes the operation of the given energy systems based on input data provided by the user, before all energy system options are simulated and compared to each other. The model covers both electrical and thermal systems, as well as transport and industrial sectors. EnergyPLAN is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University. The model is programmed in Delghi Pascal and is free of charge

EnergyPLAN focuses on the future energy system rather than the present, meaning the tool contains relatively detailed modelling of future energy technologies, while relatively aggregated modelling is used to represent the present technologies such as power plants. The focus of the EnergyPLAN is the balance between supply and demand, and the model has relatively simple representation of electricity and gas grid infrastructure. The model uses an hourly time resolution. Several different energy carriers, generations technologies and storage technologies are represented in the EnergyPLAN model. Important inputs to the model are a definition of the energy system and associated costs including demand of electricity, heat and cooling, industry and fuel, transport and water, supply of electricity, heat, fuel, waste, and CO_2, and balancing and storage of electricity, thermal and fuel. Results from the model include aggregated results for the optimal solution. Results can also be shown per year, month, or hour for each unit in the system.

3.3.5   energyPRO

energyPro is a model for techno-economic optimization analysis of various energy projects. The tool optimizes operations of the energy system based on preconditions such as weather conditions, technical properties, and all relevant system costs. EnergyPro is designed to analyse heat, CHP, process and cooling related energy projects. The model is used to optimize operation of energy plants and simulate energy plants' participation in different markets, and investment analysis.

EnergyPro include some pre-defined energy production and storage units, and it is possible for the user to define other units. Analysis are performed using a one minute time-step and EnergyPro accounts for all system costs including emission penalties. energyPRO focuses on single projects but can also consider several connected sites. The model includes a simple representation of the networks, and grid losses are modelled as a heat demand.

energyPro is maintained by EMD International A/S and is a commercial product and requires a licence.

3.3.6   ETEM

ETEM (Energy-Technology-Environment-Model) is a model developed to find the optimal energy and technology options at regional or city level [10, 11]. The ETEM model is developed by ORDECSYS. ETEM is open-source and is written in a free modelling language (GMPL), and can be linked to a free solver (GLPSOL). ETEM is part of the MARKAL/TIMES model family.

ETEM is a bottom-up model that finds the energy policy with minimal costs, investing in new equipment (new technologies), production capacity (installed technology) and import/export of primary energy in order to meet a specified energy demand of a region or city.

Key inputs to the model:
- A description of the current system
- An estimate of the demand, and the evolution in demand within the analysing period
- A catalogue of technologies, including technical parameters, costs, and boundaries.

The model also includes emissions either as a constraint or emission taxes. All costs are considered including investment costs, operational costs, maintenance costs, and emission taxes. ETEM can also deal with uncertainty in some input data by using the tool DET2STO which is another software tool for generating a stochastic program.

Several different energy carriers are represented, including electricity and district heating. Most relevant conversion, storage and end-use technologies are also represented.

The time resolution is flexible. The analysing period is split into periods of two to five years. Each year is split into typically four seasons, and each season is split into typical days and typical day parts.

In ETEM, network losses are only considered by using a fixed efficiency. In an updated version of the model, called ETEM-SG (for Smart Cities), both transmission and distribution networks are represented by simplified DC power flow and linearization of power loss equations. District heating networks are also modelled.

3.3.7   GTMax

GTMax (Generation and Transmission Maximisation Model) models and analyses the dispatch of electric generating units taking into account limitations in energy resources and transmission capability. In addition, the model also considers firm contracts, independent power producer agreements, and bulk power transaction opportunities on the spot market. The model is typically used

at national scale and can simulate both the electricity sector and district heating networks. The objective of the model is to maximise the net revenue of the power system. GTMax uses an hourly time-step. The model can also be implemented in real-time operations with connections to SCADA systems. GTMax is maintained by Argonne National Laboratory and requires a license.

3.3.8 HOMER

HOMER (Hybrid Optimization of Multiple Energy Resources) is an economic tool for rapid assessment of least cost solutions for clean reliable power. HOMER was originally intended to be a platform for analysing microgrids in villages and developing areas, and small islands. The scope of the model has expanded and HOMER is now capable of performing analysis for a wide variety of distributed generation scenarios. One of the goals of HOMER is to ease communication between different micro-grid actors, such as power engineers, utility operators, financers, and renewable advocates. HOMER was developed by the National Renewable Energy Agency in USA, but is now managed by HOMER Energy LLC and is a licenced product and includes several different modules that are continually updated.

The user starts by specifying the electric and thermal loads in the system. Electrical loads can be specified either by importing time series, or by using pre-set generic load profiles included in the model. The user then specifies a set of investment alternatives regarding generation and storage technologies. HOMER includes a product database with generic models of the most common components, including technical data and prices, and a wide variety of technologies are available. The model can automatically download solar and wind resources based on the location specified by the user. Sensitivities can also be specified on a number of the input parameters. HOMER does not model the electricity or thermal grid. The model then simulates all possible combinations of investment alternatives over one year and uses a time step of minimum 1 minute. All the investment alternatives for all sensitivity cases are then ranked based on performance.

3.3.9 Mesap PlaNet

Mesap (Modular Energy-System Analysis and Planning Environment) is an energy system analysis toolbox, and PlaNet (Planning Network) is a linear network model for Mesap. Mesap PlaNet is designed to analyse energy supply, demand, costs, and environmental impacts for local, regional, national, and global energy systems. It is possible to specify the time-step from 1 minute to multiple years. The model has previously been used for global and national energy system analyses. Mesap PlaNet is maintained by Seven2one Informationssysteme GmbH, and the models require a license.

3.3.10 MODEST

MODEST (Model for Optimisation of Dynamic Energy Systems with Time dependent components and boundary conditions) is an energy system optimisation model that calculates the best way to satisfy the energy demand with existing or new equipment. The objective of the model is to minimize the capital cost for new installation and all operational cost over a specified number of years. This is done by using linear programming. MODEST was developed as part of a PhD thesis [12] and is now managed by Optensys Energianalys.

The model includes several different energy carriers, including electricity and district heating.

Equipment can be modelled with a chosen level of detail. Typical inputs to the model includes efficiencies and revenues, and plant and storage capabilities. MODEST uses a flexible time resolution where each year is divided into seasons, and each season is divided into periods representing any set of hours. Distribution losses are represented by a specified efficiency.

MODEST results include:
- Best use of energy carriers and demand-side measures in each time period
- Optimal types, sizes and occasions for investments
- Time-dependent marginal cost for covering demand
- Total cost and annual cash flow of costs and revenues
- Emissions
- Duration diagram of energy supply

MODEST has mainly been used to analyse electricity and district heating supply for local utilities.

3.3.11 SIFRE

SIFRE (Simulation of Flexible and Renewable Energy Systems) is a simulation tool developed by Danish transmission system operator for electricity and natural gas, Energinet [20]. SIFRE is a market simulation tool developed to analyse future behaviour of highly flexible and integrated energy systems. SIFRE is the successor of the SIVAEL (SImulating heating ("VArme") and ELectricity) model.

SIFRE simulates the behaviour of the Nordpool market with an hourly timestep. The model is quite generic and not restricted to specific energy carriers, but is able to represent different energy carriers, generation technologies, and energy storage.

3.3.12 STREAM

STREAM (Sustainable Technology Re-search and Energy Analysis Model) was developed for the "Future Danish Energy System" project, carried out by the Danish Board of Technology. The purpose of STREAM is to give a quick insight into potential energy mixes for defined regions or countries and to create scenarios on demand. The model consists of three spreadsheet tools: energy flow tool, energy savings tool, and duration curve tool. STREAM uses a bottom-up approach and does not perform any economic optimisation. The model is maintained by the Danish company Ea Energy Analyses, which distributes the model for free.

3.3.13 TRNSYS

TRNSYS (Transient system simulation program) is a transient system simulation program for simulating the performance of the energy system. TRNSYS is primarily used to analyse single projects. The time step ranges from 0,01 seconds to one hour and allows for simulation of relatively detailed operation transients. TRNSYS has been commercially available since 1975 and is currently being maintained by an international collaboration from the University of Wisconsin (USA), the Centre Scientifique et Technique du Bâtiment (France), and TRANSSOLAR Energietechnik (Germany).

4   Models developed for global and international analysis

4.1   EMPIRE

This chapter gives a description of EMPIRE (the European model for power system investments with renewable energy) [21] developed by C. Skar during his doctoral degree. In WP2 of ZEN the plan is to further develop and apply this modelling tool.

The model is used for long-term planning of capacity expansion to reduce carbon intensity of an energy system, and it is specifically designed for electricity networks on a European scale. The main idea is to represent aggregated short-term operations for different countries and investigate the consequences of international interactions on the planning and operation of the energy system. EMPIRE is implemented in Xpress-Mosel.

There are two temporal scales: one operational scale (on an hourly basis) and one investment scale (on a five-year basis). The spatial scale of the energy system is represented by a network structure of nodes and arcs (see Figure 6: Illustration of the spatial scale of EMPIRE[21]. The red arcs represent transmission cables, and the black arcs represent transmission lines.. The nodes in the network represent areas/countries of energy supply and demand, and the arcs represent transmission of energy between these areas. The model includes three categories of capacity: Generation, storage and transmission. Fresh developments also include capacity in Demand Response (DR).
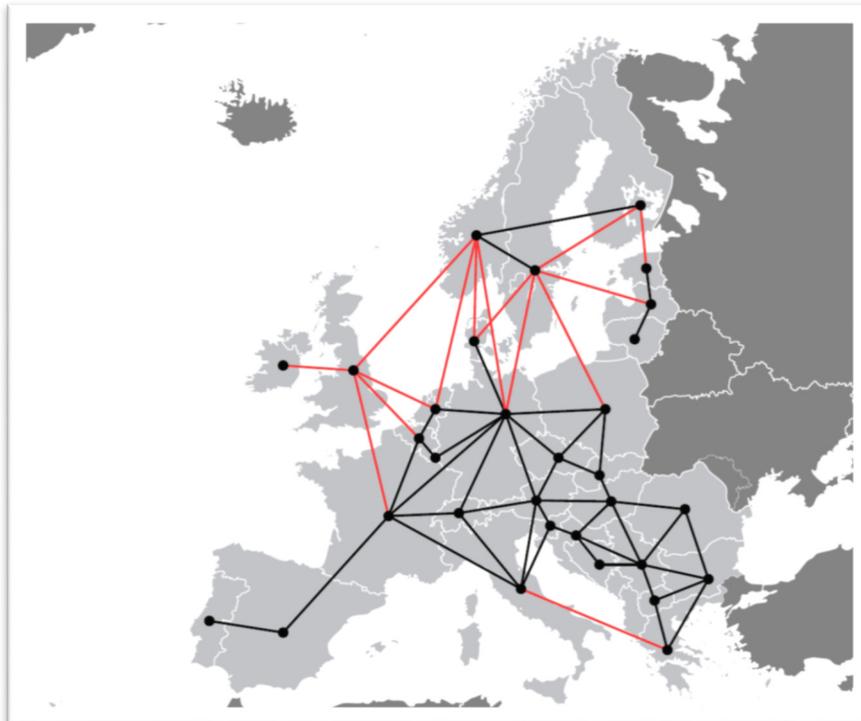

Figure 6: Illustration of the spatial scale of EMPIRE[21]. The red arcs represent transmission cables, and the black arcs represent transmission lines.

EMPIRE is a stochastic linear programming model, i.e. the model explicitly considers uncertainty in the input data and optimizes a system of linear expressions. The modelling of uncertainty is done through a set of scenarios representing possible realizations of certain factors, such that there is a unique value assigned to the stochastic input data for each scenario. These factors include availability of intermittent energy generators and energy demand. Reaction to the realization of one scenario is represented by stochastic variables linked to planning decisions, such that the model produces output that are somewhat flexible to ensure the reliability of the system with uncertainty being present.

EMPIRE has a multi-horizon structure [22]. In contrast to a multi-stage structure, the multi-horizon structure cuts significantly on the computational challenge of large instances by removing the dependency of future investment and operational decisions upon present operational decisions (see Figure 7). The multi-horizon structure forms consecutive two-stage problems only linked through the investment decisions, so the operational uncertainty of one investment period only affects that particular investment period. This means we are assuming that gaining information about uncertain operational factors does not affect future realizations of operational factors, i.e. the weather today does not tell us anything about the weather in five years. It also means that operation today does not affect investments, i.e. total energy actually produced by a solar panel is not a factor evaluated when making decisions about investing in more panels.
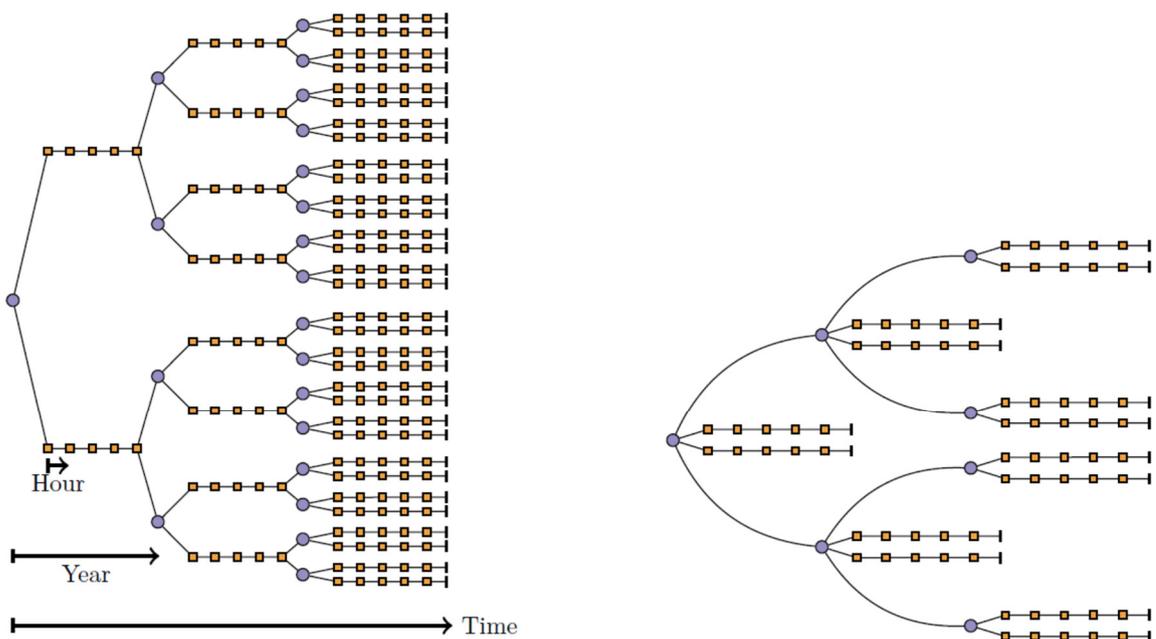
Figure 7: Illustration of a multi-stage (left) vs multi-horizon (right) stochastic structure. The blue dots represent investment decisions, whereas the orange boxes represent operational decisions.

The objective of EMPIRE is to minimize total discounted investment and operational costs of the energy system, and thus represents perfect competition in an energy market. Within the assumptions of the model, the results of EMPIRE therefore represent an ideal progression of the interconnected energy system. Because of the long-term planning horizon, the model also considers lifetime of assets.

The short-term operation of the energy system is aggregate for each node, so there are limitations to capturing the details of real operational dynamics. However, the model does address availability of certain generators, losses in production and delivery of energy and ramping of thermal generators.

4.2   Alternative models

This chapter presents some alternative models for global and international analysis of long-term planning and operation of energy systems. These models have been used to perform analyses similar to EMPIRE, with a large geographical system perspective.

4.2.1   DIMENSION

DIMENSION – a dispatch and investment model for European electricity markets [23, 24] was developed at the Institute of Energy Economics University of Cologne. The model is a deterministic linear programming model that investigates long-term expansion and short-term dispatch of generation and storage capacity of an energy system with full information about all components. DIMENSION is implemented in GAMS.

The model mainly represents the electricity system, but it is possible to represent cogeneration units serving both heat and electricity demand. It also includes a representation of demand response options. The model has been used to evaluate different energy policies and the need for grid expansion on a European level. A weakness of the model is not representing short-term uncertainty.

4.2.2   PRIMES

PRIMES [25] is formulated as a non-linear mixed complementarity problem (MCP), and has been developed since 1993 by the National Technical University of Athens. The model seeks a market equilibrium for energy supply and demand on a European level, and it has been used to create energy outlooks for the EU. It is implemented in GAMS.

The model represents different stakeholders of the European energy market, where each stakeholder makes decisions about providing supply, demand and bids/offers in the market. The model then finds the market clearing and the equilibrium in which all stakeholders are making the best of their position. The equilibrium represents technology choices and dispatch decisions as a reaction to the market subject to policies and regulations.

PRIMES has a modular design, meaning individual modules can represent different details and opportunities for the stakeholders in an energy market. Stakeholders represent sectors of demand and supply, such as industry and electricity producers. A fundamental assumption of PRIMES is that all stakeholders react to price changes.

4.2.3   EMPS

EMPS (EFI's Multi-area Power-market Simulator) [26], or Samkjøringsmodellen, has been developed by SINTEF since 1975 to plan and operate an electricity system with significant amounts of hydro power. Among other things, it calculates the optimal generation from hydro power and thermal power generation, power prices in various areas, and utilization of the transmission grid for a number of

climate years (affecting hydro power inflow, consumption, wind-power, solar-power, and run-of-river), and with a minimum within-year time-resolution 1 hour. It is in use by hydro power producers, system operations and regulators in the Nordic area e.g. to study further power system developments.

The model consists of one strategy evaluation part to calculate the potentials in regional sub-systems based on stochastic dynamic programming. The other part of EMPS evaluates optimal operation of the regional sub-systems subject to transmission constraints and demand in a linear programming framework. Investments in new capacity is a one-step methodology, e.g. from today to a given future year.
Many versions of EMPS have been developed, and the model has been used for several analyses of the Nordic power system, including price forecasting and evaluation of transmission capacity expansions.

4.2.4   ELMOD

ELMOD [27, 28] was developed at Dresden University of Technology in 2008, and is a large scale non-linear programming model of the European electricity system to optimize operation and dispatch of generators. The non-linearity stems from the rather detailed representation of line flows in the transmission network. ELMOD is written in GAMS.

Four ELMOD models have been developed since the original model. The initial ELMOD model has an hourly time scale for one day, and it represents detailed operation of the European electricity system. ELMOD-DE is a model for Germany only, and has an hourly time scale for one complete year. stELMOD is a stochastic extension of the original model to deal with uncertainties in wind production.

dynELMOD [29] is the newest development, and it is most relevant for FME ZEN because it includes investment planning on a European level. Line flows are modelled using a flow-based market coupling approach through a PTDF matrix, or through simple capacity constraints, so it has a simplified linear representation of line flows compared to the original ELMOD. dynELMOD does not consider uncertainty in operation or investments explicitly.

5   Summary and discussion

5.1   Models for WP5

Table 1: Summary of different models for local system operation and expansion.

Tool	Availability WP5	Investment optimisation	Time resolution	Geographical area	Net-work	Miscellaneous
eTransport	SINTEF Energy	Dynamic	Hour (time slice)	Local	Yes	
TIMES	Open source	Dynamic	Hour	Global/National/regional	Yes	
NTNU-model*	NTNU	One-step	Hour	Building	No	
Balmorel	Open source	Dynamic	Hour (time slice)	Global/National/regional	Yes	
COMPOSE	Free	One-step	Hour	Project	No	
DER-CAM	Free	One-step	Hour/minute**	Local	Yes	
EnergyPLAN	Free	No	Hour	National/regional	No	
energyPRO	Commercial	One-step	Minute	Local	No	
ETEM	Open source	Dynamic	Hour (time slice)	Regional/city	Yes	
GTMax	Commercial	One-step	Hour	Global/National/regional	Yes	No emissions
HOMER	Commercial	One-step	Minute	Local	No	
Mesap PlaNet	Commercial	Dynamic	Minute	Global/National/regional	No	
MODEST		Dynamic	Hour (time slice)	Local	No	
SIFRE		No	Hour	National/stat/regional	No	
STREAM	Free	No	Hour	National/state/regional	No	No operation optimization
TRNSYS	Commercial	One-step	0,01 s. – 1 s.	Local	No	No Emissions

*   Optimal energy system design for ZEB using MILP.

**   Hourly timestep is used for investment optimization and timesteps of one minute is used for operation optimization.

Font colours in Table 1 indicate the suitability for ZEN WP5. Green colour is the best assessment for the corresponding category, whereas blue is better than black. The following criteria have been used for specifying colours per category:

- Availability WP5: Green for models developed by ZEN partners, and blue for open source models.
- Investment optimization: Green for models with dynamic investment optimization, and blue for models that only optimize investments at the start of the analysing period.
- Time resolution: Green for models with time resolution of one hour or less.
- Geographical area: Green for models developed for local analyses and single project investigations. Blue for models originally developed to analyses larger systems, i.e. typical market models, but also can be used to analyse local systems.
- Network: Green for models able to represent the local electricity and district heating network. Blue for models with modelling of network originally designed to represent the transmission grid.

Black font colour is used where the models are not suited for analysing the research questions in FME ZEN WP5.

WP5 in ZEN aims to develop and apply methodologies that identify the socio-economic optimal operation and expansion of energy systems within demarked areas. In order to further develop the models described in this report access to the source code is necessary. Out of the 16 models assessed in this report, eTransport developed by SINTEF Energy Research and Optimal energy system design for ZEB using MILP developed by NTNU, are the only models developed by ZEN partners. In addition, two of the models are open source: Balmorel and ETEM. The possibility to further develop the models to include new innovations are especially important in a research project such as ZEN. Access to the source code will also give better control over the assumptions and the simplifications made in the modelling of the energy system, and could allow tests to check whether the assumptions are valid.

The pilot cases in ZEN include both development of new ZEN and development of existing areas up to a ZEN standard. In both cases the energy demand and hence the need for energy system investments develop over time. Many of the models considered in this report optimizes investments only in year one. Only eTransport, TIMES, ETEM, MODEST, Balmorel, and Mesap PlaNet also considers the optimal timing of the investment based on the development in the demand within the lifetime of the projects.

In some cases, losses in local infrastructure might lead to significant costs and is therefore important to model when considering operation and expansion of local energy systems. Electrical losses are proportional with the square of the current, thus some simplifications are necessary to model electrical losses in a linear model. Modelling electrical losses by a fixed efficiency might be too simple in some cases. Development of existing areas to a ZEN standard might impose investments needs in the electrical and district heating network due to increased loads and/or local production. It is therefore important to model limitations in local infrastructure to capture theses investment needs. This is also the case when developing new ZENs, but in these cases, the local infrastructure should be dimensioned to handle the future energy demand. Six of the models includes modelling of local networks, although some only have very simple network representations.

Ability to consider greenhouse gas emissions are naturally important in FME ZEN, and almost all the models considered in this report consider greenhouse gas emissions.

In most cases the tools considered in this report model loads using a fixed consumption profile. Planning tools for the future energy system should also be able to take into account new possibilities for forecasting, modelling and control and also consider flexibility, virtual storage, and demand response. This is not considered in this report, but will be considered in the future work.

Of the assessed models, ZEN partners are the developers of two of them: eTransport (SINTEF model) and the NTNU model. The further development of both of these were foreseen in the ZEN application. As shown in Table 1, eTransport performs well at the applied assessment criteria, and the model will be further developed in FME ZEN and used to analyse ZEN pilots. Furthermore, the NTNU model that initially was developed in FME ZEB will be further developed by PhDs in FME ZEN. This will

give an important continuity for the research activity regarding local models for the NTNU, and the model should also be applied on ZEN pilots, and possibly utilize the complementarity with eTransport with its focus on systems within buildings. Based on our assessment – and the limited amount of budget available – we do not currently foresee that it will be economically efficient, practical, nor necessary, to also apply or develop additional local energy system models within WP5 of ZEN. However, we also want to utilize synergies with model developments for local energy systems and their use in other parts of ZEN, including

- In WP3 - HOMER model with a focus on buildings
- In WP4 – detailed and statistically oriented models for local energy solutions

5.2   Models for WP2

Table 2: Summary of energy system models with an international perspective.

Tool	Availability WP2	Short-term uncertainty	Long-term uncertainty	Time scales	Network	Model type
EMPIRE	NTNU	Yes	Possible	2	Yes	SP
DIMENSION	-	No	No	1	Yes	LP
PRIMES	-	No	No	1	No	NLMCP
EMPS	SINTEF Energy	Yes	Myopic	2	Yes	SDP/LP
dynELMOD	Open source	No	No	2	Yes	LP

Table 2 summarizes the models that deal with energy system planning from a top-down perspective. In addition to the models in Table 2, TIMES, Balmorel, EnergyPLAN, GTMax, Mesap PlaNet, SIFIRE and STREAM from Table 1 could also fall into the category of top-down models.

A central research question for WP2 in FME ZEN is: What is the cost-optimal development of the interconnected energy system under different policy scenarios and uncertainties when there are possibilities of developing ZENs? To answer this, we need a top-down stochastic model that somehow also deals with a local spatial scale for investments and operation. The model basis provided by EMPIRE could tackle this question, but some new developments must be made. The main benefits of continuing with EMPIRE in FME ZEN include easy access to source code through NTNU and a good representation of uncertainty through the multi-horizon stochastic framework. Considering uncertainty in short-term operation of intermittent generation technologies has been shown previously to have high impact on the results [30].

There is a great potential of further developing EMPIRE to represent ZENs on an aggregated level and thereby create a model that could investigate larger system effects of introducing ZENs. This development includes somehow representing ZENs within each node of the spatial network. The representation of ZEN could be through a new spatial scale, e.g. a new network within each node. Possibilities of investing in local generation and storage capacity will be present in these representative neighbourhoods.

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