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for Economic Affairs
and Climate Action

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Energiepartnerschaft
DEUTSCHLAND - CHINA

DIGITAL TOOLS FOR THE DEVELOPMENT OF CLIMATE NEUTRAL DISTRICTS

Sino-German Demonstration Project on Energy Efficiency in Cities

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1 Executive Summary

This report concludes a study into digital tools and processes involved in decarbonizing new and existing districts. As part of this process, the author examined workflows being used around different parts of the practice and shared their findings in two workshops under the framework of Sino-German Demonstration Project on Energy Efficiency in cities.

The exact definition of "carbon-neutrality" was not the focus of this analysis, however, it is the starting point of any discussion and should be determined at the start of every project based on what is realistically achievable under current best practice.

A main challenge of planning low emission districts is providing useful information to make decisions early in the design process and managing this information across project phases and disciplines in an integrated design process. This contrasts to typical practice today where planning tasks are split contractually among disciplines that often do not share the same project goals and sometimes fail to share important project information. The software landscape is similarly fragmented, where complex multi-purpose packages compete with very task-specific ones with clearly defined goals, and information transfer between packages is generally poor unless interfaces are intentionally designed.

This report analyses different solutions by looking at them through the lens of a project lifecycle. The outcome is an idealised process with tool suggestions, which may be appropriate to the given stage. All the tools mentioned in the report are only exemplary solutions, most of them have been well proven in the practice of the author in the field of energy consulting. However, they do not represent the overall picture of current software tools and should not be interpreted as the exclusive solutions on the market.

The study work took place from September to December 2022, and was split into three packages, which main findings are covered in chapters 3, 4 and 5 of this report. In the first work package, the author provided an initial overview of software tools available on the market for the individual project phases, comparing the application areas, calculation and optimization methodologies, compatibility, and other important features for planners. In the second work package, the author offered a vision of a planning process and corresponding tools for achieving low emissions districts. In the third work package, two workshops have been conceived and conducted with experts from research institutes and industrial providers, with the first in Germany (hybrid) and the second in China (virtual). The presentations were highly participatory, and the observations and recommendations made on the previous two work packages are incorporated in the later sections of this report.

The applied investigation and expert exchanges showed that there is no silver bullet to address all application cases in the context of urban development and the planning or industrial parks or districts, although a large number of specific software solutions is available in the market. The importance of consistent data management and communication throughout the project was highlighted. A promising solution to support these needs is seen in urban digital twins, allowing for holistic data representation as well as bidirectional communication between real objects and their digital representation. An outlook on further development opportunities is provided in up in chapter 6 of this report.

Source: 699pic.com

2 Project context and objectives

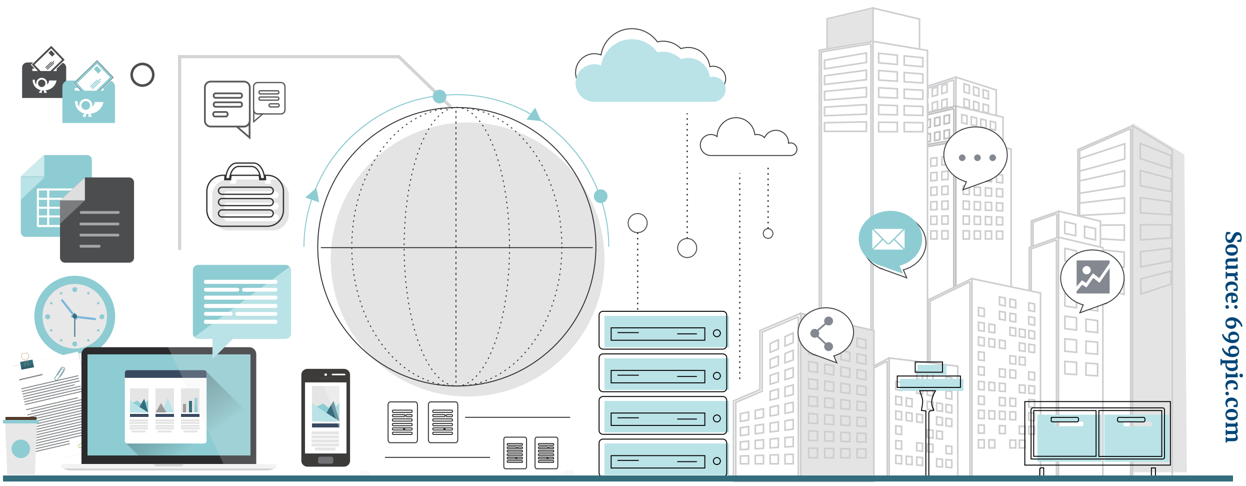
To achieve climate neutrality, private and public companies, as well as citizens, need to work together to create new emission-free ecosystems in cities. The integrated district approach comes into play here as the district is the most effective level, at which the problem can be tackled and climate neutrality achieved. As the largest manageable unit, districts create synergies between several end users and individual stakeholders, bundling local potential. These synergies can be used to couple the energy and end-use sectors. Combined mixed-use of infrastructures can significantly reduce costs and lead to new business models.

Climate neutral districts have to be developed in an integrated process. Numerous decisions have to be made on very different levels by different interest groups and actors. Within the optimisation process, energy savings, power generation, sustainable construction, investment and lifecycle cost, legal regulations for the energy sector, tenancy laws, energy prices, funding, financing and many other aspects have to be aligned to identify the best fitting solution. The specialised planning tasks require a number of disciplines to contribute to the common goal of climate neutral districts. Therefore, in the planning and implementation processes a number of digital solutions are used, and many software tools are designed for single aspects and follow different calculation standards. That is why they cannot be linked to each other and do not necessarily work together in a harmonized process, which would create synergies and enable system optimization.

To get a holistic overview on different parameters, a number of tools have to be used in extremely time-consuming calculation processes, which is not feasible in practice. To weight all the potential technical solutions or products, choose the most suitable ones and integrate them into a system, it is necessary to have a clear and simplified structure of planning and calculation tools basing on holistic thinking, but this clear structure is not yet available.

Within research and analysis, we propose to consider the whole process of the development of climate neutral districts, including planning, implementation and optimization of operation. With three parts of working contents, we are aiming to create a clear structure as guidance to support the development of climate neutral districts with dedicated energy planning and evaluation tools.

This work was carried out within the framework of the Sino-German Demonstration Project on Energy Efficiency in Cities initiated by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) and the National Development and Reform Commission of the PRC (NRDC). It was jointly implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, the German Energy Agency (dena), and the China Energy Conservation and Environmental Protection Group (CECEP). The content is derived from a work process that took place in the second half of 2022 under the conceptual leadership of the German Energy Agency (dena). The consulting firm Buro Happold provided practical foundations for technical aspects.



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3 Status Quo

3.1 Introduction

The built environment is responsible for 39% of global energy related carbon emissions: 28% from operational emissions, from energy needed to heat, cool and power them, and the remaining 11% from materials and construction[1].

Germany and China aim to be carbon neutral by 2045 and 2060 respectively. According to the IPCC, the world needs to reach net zero by 2050 to stay in line with the 1.5°C target[2]. These targets and carbon budgets for different sectors have not yet been transformed to quantified requirements for specific buildings; at the time of writing non-binding target values are suggested by QNG in Germany[3]. Meanwhile, there is an urgent need to treat emissions from building operation and construction in the same way we treat financial cost in the current processes.

Many tools are already available not just to help design systems which work, but to also explore multiple alternatives and pick the option with cost-optimal solutions. If emissions are also treated as a cost and included in this process, all these existing tools and any future process innovations will also improve the path to decarbonise the built environment.

3.2 Status Quo vs. Ideal Situation

The Figure above (based on the German situation) illustrates the project phases and key players for a typical project. The relationships and length of involvements are project specific: planning teams may be fully integrated with other consultants or not at all, and third-party project managers/ coordinators acting on behalf of the client are typical.

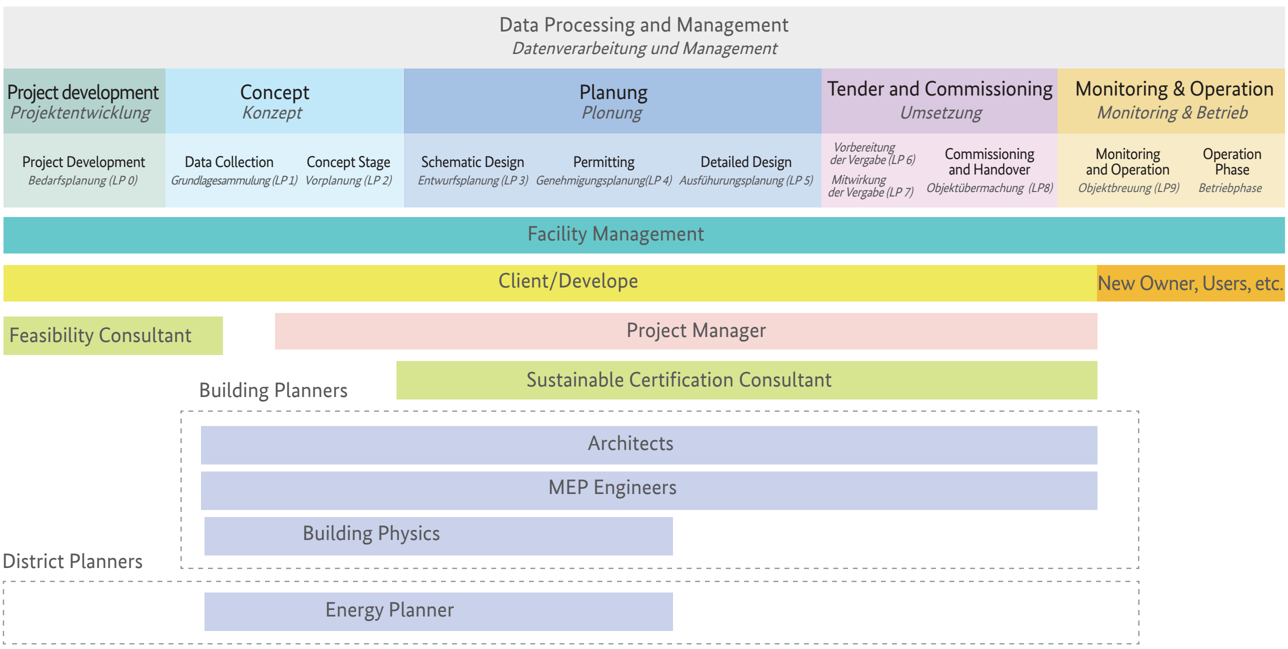


Figure 1 Players within the project boundary with influence over the energy planning process (non-exhaustive, own illustration)

1 World Green Building Council: https://worldgbc.org/advancing-net-zero/embodied-carbon/

2 The Intergovernmental Panel on Climate Change (IPCC): https://www.ipcc.ch/sr15/chapter/chapter-2/

3 Federal Ministry of Housing, Urban Development and Building: https://www.nachhaltigesbauen.de/fileadmin/pdf/QNG-BEG/QNG_Handbuch_Anlage-3_Anhang-3212_LCA_Anforderung-NW_v1-2.pdf

A successful project requires all designers and specialists to be engaged early enough, so that the result of their work does not undo any work done by other parties. It is critical that all participants contractually and technically are enabled to easily exchange information with one another. Herein lies the question, which the author explored in this report: Is there a “super-tool” which can cover all stages of the design process?

In Germany, around 80% of the building stock of 2050 already exists today. This means that most district energy projects will deal with refurbishing and decarbonising existing assets. Refurbishments require additional steps compared to new construction projects such as data on operational energy and existing systems.

When decarbonising existing assets, it is therefore far more effective to use measured data as a starting point to understand demand, emissions, and opportunities to decarbonise. While this report does not cover this data acquisition and processing stage, mention is given to building monitoring packages.

3.3 Software Matrix

After looking at the different roles and processes in low-carbon design, the author compiled a list of packages used throughout the design process and compared several of their features in a “Software Matrix” (see Figure 2). Most of the tools specialise in specific parts of the design process such as building energy modelling or techno-economic evaluation of energy supply systems at regional, national or international scale.

3.3.1 Overview on general approaches of existing solutions

No single package was identified, which excels at modelling both building and urban systems. However, some general approaches exist in which software solutions solve specific planning tasks: building-scale packages tend to have limited geometry builders and rather interface with CAD platforms better designed to create 3d models. Urban-scale packages tend to interface with GIS platforms. Some urban-scale packages have some form of load profile generator using building archetypes or r-c models but also offer the option to import an externally generated profile. There are also some examples of general-purpose CAD or GIS platforms with calculation add-ons, which run either internally or through some other third-party package.

Few packages were identified, that could be used over the whole building lifecycle and contain early concepts, detailed designs, simulation results, measured data and act as a monitoring tool.

In order to create a comprehensive assessment of the different characteristics and point out common or distinguishing features a matrix (Figure 2) was developed describing software solutions and their features for a better comparison. Solutions were clustered in the groups “Building Energy Modelling”, “District Energy Planning Tools”, “Data Integration Tools” and “Operational Tools”.

Features included in the assessment (Figure 3) are among others the related goal or Task, the underlying methodology (i.e. optimisation or simulation) the temporal resolution as well as the scope.

Filter	Building Energy Modelling				District Energy Planning Tools				Data Integration Tools				Operational Tools			
Goal																
Resolution																
Methodology																
Interfaces																
Scope																
Transparency																
Eenrgy Sources																
Technologies																
Financial																
User Experience																

Figure 2 General Structure of the software matrix

Goal	Resolution	Methodology	Interfaces	Scope	Transparency	Energy Sources	Technologies	Financial	User Experience
Defined goal	Spatial	Simulation Approach	Interfaces to other software, tools and databases	Planning	Access to the calculations	Integrated geographical and environmental data	Extent of Technologies which can be modelled	Integrated financial calculation	Installation requirements
Use Cases	Temporal	Optimisation methods	Interface with BIM models	CO2-Bilanz Scope (LCA)	Ability to export input data for validation	Ability to calculate renewable energy from different sources	Network modelling	Considers CAPEX or OPEX	Advantages over other Packages
Integrated Norms and Standards		Optimisation goals		Sectorcoupling	Energy balance scope		Ability to model storage	CAPEX: Linear or dynamic?	Limitations and Disadvantages
								OPEX: Static or dynamic?	Costs
									User access to inputs and results
									Number of users/ Collaboration

Figure 3 Categories used to assess the individual packages

3.3.2 Build an in-house tool?

Decarbonisation will require more intense monitoring of projected emissions against targets and better coordination between disciplines in achieving these targets. How far can a combination of existing tools help design teams overcome the challenge of decarbonisation, and what exactly is needed to solve the problem? The next section will go through an idealised process to design low emission districts, including how various packages featured in the software matrix can be used in the different stages. Still, there is scope and need for innovation, especially in terms of interoperability and parallel optimization of costs, performance and emissions. The table below explores some of the trade-offs for planners and developers of developing tailored in-house solutions versus adapting commercial packages to achieve these goals.

	„Off the shelf" Packages	In-house Solutions
Advantages	Pre-programmed functions save time	Absolute control and full access to calculations and data
	Higher complexity possible	Easy QA and validation
	User-friendly interface, IT support, constant updates and maintenance	Can fulfil very specific needs
		Can interface with other workflows as needed
		No licencing fees
Disadvantages	Less customizable and flexible, some project specific features - special features or constraints cannot be modelled	Time and Resource intensive to develop and maintain
	„Black box" - Limited access to calculation procedures and data sources	Tools need instructions, maintenance and updates - may not be user friendly
	Disadvantages for QA and data validation	Requires professional and technical know-how which may not be available
	Data transfers often requires interface (e.g., Excel) and manual data linking	
	License fees	

Table 1 Building an in-house solution versus purchasing a commercial package

4 Designing a Climate Neutral Urban District

After getting an overview on general approaches of existing software solutions and the most important features of them, a more in-depth analysis along the whole process and each individual project phase could be done. In this chapter, with selected exemplary software tools, the author offers a vision of an optimised planning process and corresponding tools for achieving low emissions districts.

4.1 Guiding principles

Designing a climate neutral district is a complex, interdisciplinary and iterative process that requires extensive cooperation, interaction and information exchange. To support the planning process, the author summarized the following guiding principles for design tasks from the perspective of an energy planner:

- Identify objectives and scope of climate neutrality
- Set up emission targets and align with national targets including embodied carbon
- Feasibility study for sustainability, economic performance and available technologies
- Establish techno-economic model and find the optimal solution to achieve the targets
- Simulate different scenarios and create a roadmap for the implementation of measures

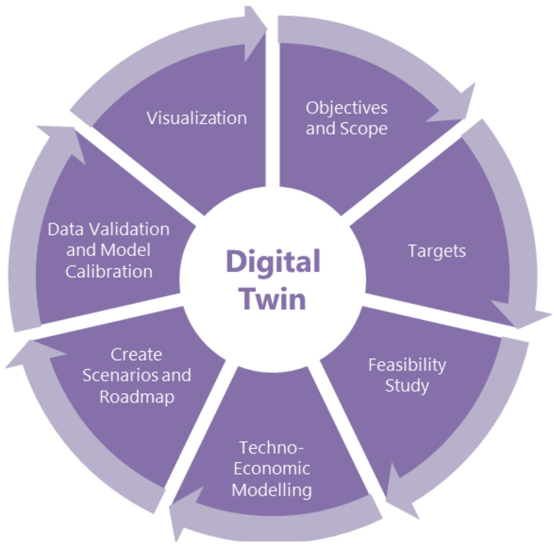


Figure 4 Guiding principles for designing a climate neutral district (own illustration)

- Data validation and model calibration to avoid over- or undersizing the energy system
- Visualization of results for better communication with developers, planners and the public
- Monitor the project long-term using a digital twin and ensure all targets can be achieved.

Source: 699pic.com

4.2 Process

This section explores how the optimal planning process of a climate neutral district should look. Figure 5 shows a standard project development, which is typically split into five stages – project development, concept, planning, construction, and operation. According to German fee schedule for architects and engineers (HOAI), the five stages can be subdivided into nine phases (LPH0-9). Following the five project development stages, the planning process can be divided into five steps –Pre-Concept, energy concept, schematic design, detailed design and monitoring. Tasks typically carried out by architects and engineers linked to the construction process such as site supervision are not included in the scope of this report. The main tasks or purposes for applying different software tools in each step are described below.

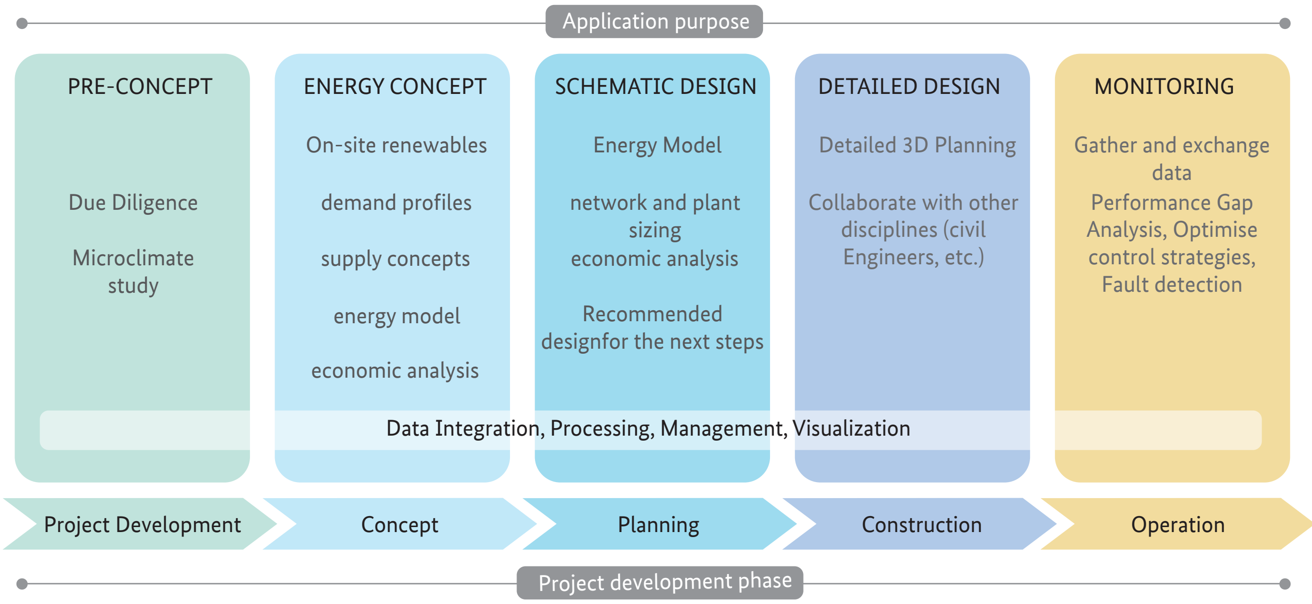


Figure 5 Planning process and purpose along project development phase in Germany (own illustration)

In the **pre-concept phase**, the following tasks should help to set up the proper framework and targets. Due Diligence checks are important to identify objectives and scope of climate protection and adaption, set up developer climate targets including energy, emissions, resilience etc., and evaluate environmental, financial, and technical feasibility. In the preliminary microclimate study, the climate risks will be evaluated, design guidelines will be made to mitigate the risks.

Application Cases

- Due Diligence: evaluate climate protection and adaptation measures, finance/budget, existing assets
- Preliminary microclimate study: climate analysis based on present and future scenarios ("Deutsche Wetterdienst" provides weather files for 2015 and 2045).

The **energy concept** phase should include investigations into all potential on-site renewables and demand profile analysis. Better quality data during this stage is necessary to make bold decisions to decarbonise, so money and effort spent doing site tests and acquiring measured data from any existing buildings are well worth it. The main tasks include data acquisition, energy modelling and economic analysis. Preliminary system dimensioning and cost estimates are essential indicators for decision makers at an early stage. The results of these analyses should be compared to the targets set up during pre-concept and if necessary, the targets may be adjusted. The outcome of this phase should be a set of energy supply options demonstrating the trade-offs between cost and emissions. This should provide the client with enough information to choose an option to be further developed in the next phase.

Application Cases

- Environmental potential analysis: analyse renewable energy sources and grid-connected energy sources
- Energy demand profiles and peak loads: use archetype/benchmark or data from simplified building simulation or accurate building and meter data
- Energy supply concepts: develop different variants
- Establish energy model: energy system optimization
- Economic analysis: evaluate economic performance of the energy system.

In the **schematic design phase**, the energy model is revised and developed further in response to other changes in planning. This process is iterated until the input parameters are matching the needs. The next step is to dimension the networks and plants based on a simulation of their performance – currently done using a set of specialized software tools. GIS mapping can help to better understand the environmental impacts and thus help to design network routes. The layouts and space requirements will be determined at this stage. Finally, the economic model is updated.

Application Cases

- Energy model: develop and optimize energy concept
- Network and plant sizing: dimension heating/cooling/electricity networks and energy plants
- Economic analysis: evaluate economic performance of the system

The **detailed design** involves coordination with planners from other disciplines. The results from schematic design are delivered to mechanical, electrical and plumbing services (MEP) and civil engineers for spatial design and 3D planning.

Application Cases

- Detailed 3D planning: spatial design of networks and energy centres
- Collaborate with other disciplines: interface between energy planners and MEP/civil engineers

During the **monitoring phase**, the main task is to aggregate, process and integrate data from sensors or building management systems (BMS) to reduce performance gaps between design and real performance, detect system faults and optimize control strategies. However, data integration and management is an ongoing process throughout the project lifecycle and helps reduce data losses between different design stages and planning teams. Data generated in different design phases, including the monitoring phase, can be integrated into a digital twin that tracks and reflects the entire planning process in a highly organized and effective way. This helps the different participants to better communicate and ensure that project targets are met.

Application Cases

- Gather and exchange data: aggregate meter data
- Performance gap analysis, optimise control strategies, fault detection
- Data integration, processing, management, and visualization

In the following sections, the author provides a brief introduction to software tools used in each design phase and for different application purposes. Important inputs and outputs will be listed to better understand modelling requirements.

4.2.1 Project Development/ Pre-Concept

Irrespective of a project being a new development or an existing asset, any business plan requires a sound understanding of what exists and the potential of the site. Besides a sound financial business model, it is also common practice for developers to commission technical feasibility studies and develop technical project requirements to reduce emissions or fulfil an Environmental, Social and Governance (ESG) framework. Demand for these studies is becoming an increasing prerequisite for access to public and private finance.

Technical and Operational

The operational Emissions of an existing asset should be evaluated using methods such as consumption-oriented allocation according to ISO 14065[4] or ISO 16745[5]. This consumption should be benchmarked against comparable building data or predictive models if any are available to identify and solve any performance gaps. The facility management should undertake a risk management assessment according to GEFMA 192.

A condition description of the existing asset should provide access to maintenance logs, notes on third party usability, technical examination of lease contracts, a data room audit and detection of any damage and defects with photo documentation. An operating expense (OPEX) forecast of the existing asset will provide a comparison baseline for any consequent work, while a technical residual life assessment will serve as a baseline for capital expenditure (CAPEX).

At this stage, it is also advisable to select a building certification scheme in line with the market and project ambitions. Some schemes offer pre-checks to estimate the cost of achieving different scores, and some require post-occupancy validation to award performance-based certification.

Financial

Part of financial due diligence should include a review of requirements for sustainable public and private financing tools, including national incentive programs. For real estate portfolio holders, tools like the EU's Carbon Risk Real Estate Monitor (CRREM)[6] help understand climate risks for value of their assets and provide some basis for strategic investment.

Lifecycle Emissions

The developer must determine a budget for embodied and operational emissions and define a system to split this budget between the various disciplines in the design process. At the time of writing, DGNB (German Sustainable Building Council) offers some non-binding targets for lifecycle emissions, however, these targets only address operational emissions indirectly by referring to emissions according to energy certificates. More work is needed at state level to align emission targets for buildings and districts with national decarbonisation targets.

Climate and Site analysis

The climate is an important parameter determining buildings' energy use, but building geometry and systems also have an impact on the outdoor climate and surroundings, that especially in residential areas should be considered during the design phase. Climate due diligence should cover present and future climate conditions, highlight strategies for outdoor comfort, good daylighting in buildings for people, massing and glazing ratios, and other resilience topics such as flood and fire risk which can affect access to finance and insurance.

Tools
- Microclimate studies: CFD7, Rhino[8] + Grasshopper[9]
- Due Diligence: Spreadsheet + Certification guidelines

4 ISO 14065, General principles and requirements for bodies validating and verifying environmental information: https://www.iso.org/obp/ui/#iso:std:iso:14065:ed-3:v1:en

5 ISO 16745, Sustainability in buildings and civil engineering works — Carbon metric of an existing building during use stage: https://www.iso.org/obp/ui#iso:std:iso:16745:-1:ed-1:v1:en

6 CRREM is abbreviation of Carbon Risk Real Estate Monitor. Please refers to the website https://www.crrem.eu/

7 CFD is abbreviation of Computational Fluid Dynamics

8 Rhino stands for Rhinoceros, which is a commercial 3D graphics and CAD application software.

9 Grasshopper: Grasshopper is a visual programming language and environment that runs with Rhino.

Input
- Climate data (weather file)
- Local infrastructure and energy sources (from regional or national platforms)

Output
- Geometry (from GIS data, 3D Model, plans, etc.)
- Evaluation of different heating and cooling strategies
- Local renewable energy potential
- Massing recommendations to improve energy efficiency and outdoor comfort.

To analyse the local renewable energy potential, different tools are available depending on the level of detail of input and output data. To calculate PV generation on a high level, it is helpful to use annual global solar radiation according to DIN EN 15316-4-3, or web-based calculators such as PVGIS. For more detailed results with higher resolution, there is simulation software such as grasshopper that can simulate panel-specific performance at building level (s. Figure 6).

The same logic applies to the calculation of energy load profiles. For a high-level analysis, using urban-scale energy software would be the proper choice, e.g. District energy

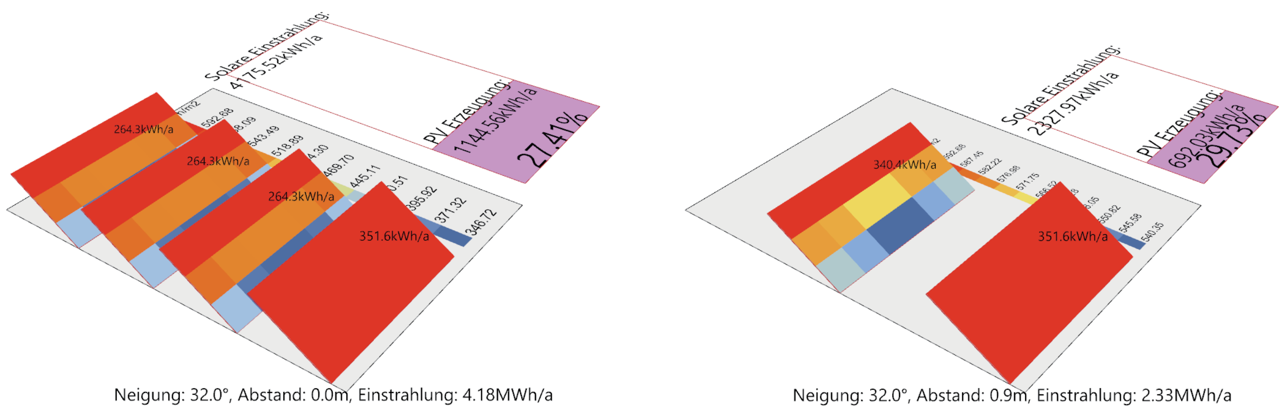


Figure 6 Advanced method to calculate panel specific radiation and PV power in grasshopper , illustrated by authors

4.2.2 Energy Concept

The energy concept for a given site describes the current or future energy needs as well as regional or on-site renewable energy potentials to meet these needs. Typically, it therefore includes targets on building energy efficiency as well as end energy and primary energy needs as well as the related greenhouse gas (GHG) emissions.

concept adviser. It can calculate annual energy intensity (kWh/m²a) according to different building types and energy standards. Other software developers provide standard load profiles of different building archetypes, such as Sympheny for urban energy optimisation and iCD IES for urban energy design and early stage master planning.

However, with sufficient time and budget, it is recommended to use more accurate energy load profile data. It can come

10 DIN EN 15316-4-3 Energy performance of buildings - Method for calculation of system energy requirements and system efficiencies - Part 4-3: Heat generation systems, thermal solar and photovoltaic systems: https://www.din.de/de/mitwirken/normenausschuesse/nhrs/veroeffentlichungen/wdc-beuth:din21:257459119

11 PVGIS (Photovoltaic Geographical Information System): https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP

12 District energy concept adviser is a software to support actors in the field of urban planning during the first stages of planning energy-efficient district concepts: https://www.district-eca.com/index.php?lang=en

13 Sympheny offers energy planners & energy managers a subscription-based SaaS platform: https://www.sympheny.com/#1

14 iCD（Intelligent Community Design）is a plug-in for SketchUp: https://www.iesve.com/products/icd

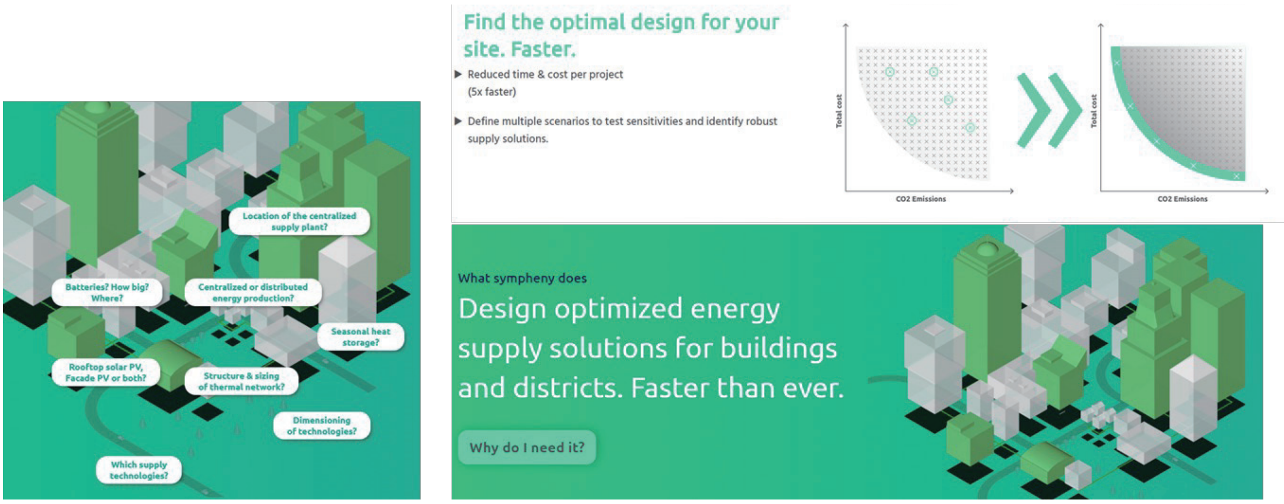


Figure 7 Sympheny urban energy optimisation tool (Source: Urban Sympheny AG. Sympheny | Urban Energy Planning, accessed 07/12/2022 from www.sympheny.com)

from building level simulations or meter data from existing buildings. Appropriate building simulation tools are e.g. IDA ICE[15] for indoor climate and energy or VE IES[16] for accurate whole building performance simulation.

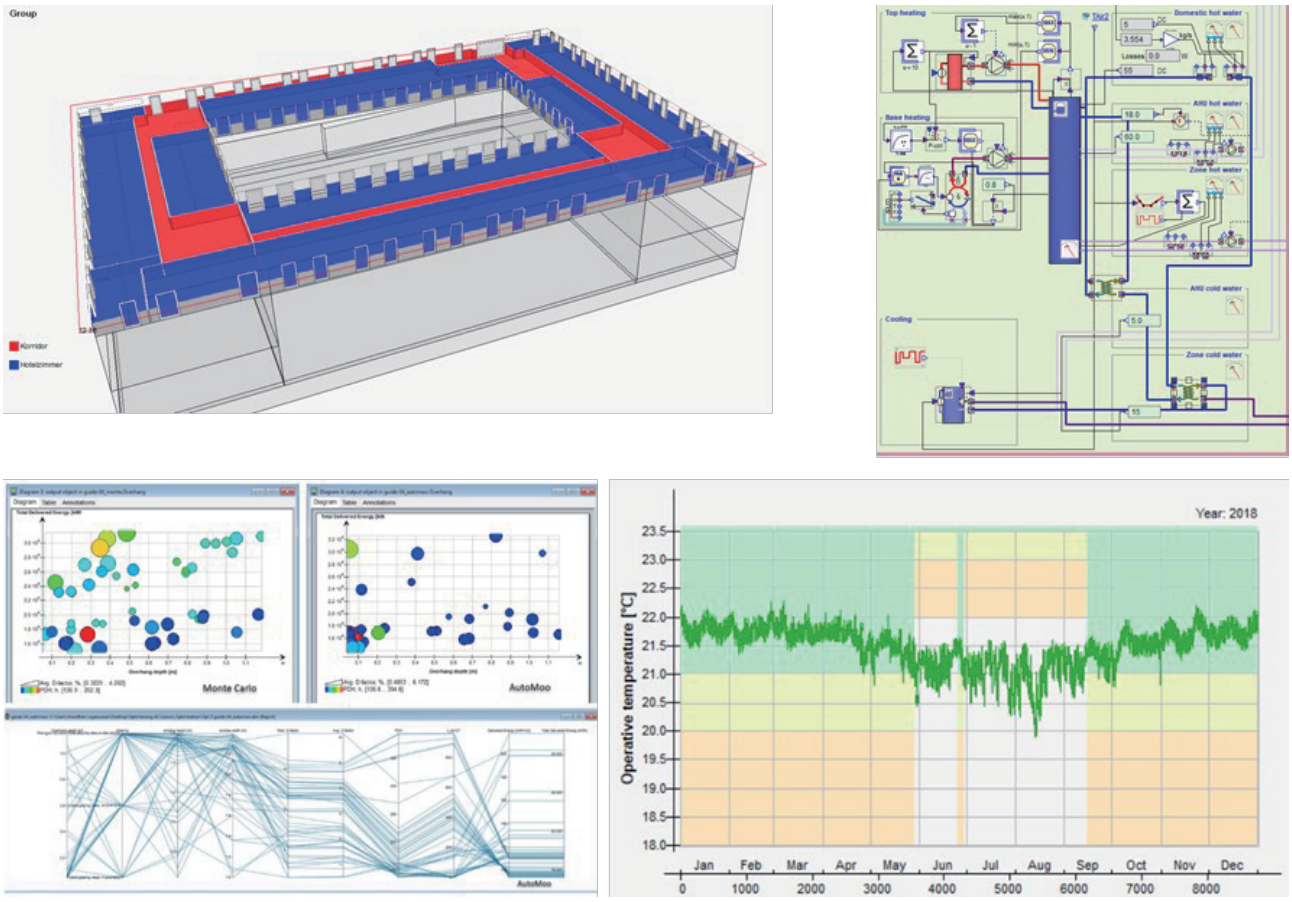


Figure 8 IDA ICE for indoor climate and energy simulation (Source: IDA ICE Training material © EQUA Simulation AB)

15 IDA ICE（IDA Indoor Climate and Energy） please refers to website https://www.equa.se/en/ida-ice

16 VE IES is the leading integrated suite for accurate whole building performance simulation, please refers to website https://www.iesve.com/software/virtual-environment

After analysing local renewable energy sources and load profiles, the author uses the software Sympheny to simulate different energy supply variants to find the optimal solution. Following input- and output-data is essential for the energy modelling:

Energy modelling in Sympheny

Input
- Energy demand from benchmarks (kWh/m²a) and load profile (kW) or
- (more accurate) demand und load profile from simulation or meter data
- Building area and typology
- Profile of renewable energy sources (kW)
- Cost benchmark CAPEX (€), OPEX (€/kWh)
- Emission factors (kg CO_2eq/kWh)

Output
- End energy demand (kWh/a)
- Generated renewable energy (kWh/a)
- Plant capacity (kW) and storage capacity (kWh)
- Autarky level
- Annualized Cost CAPEX and OPEX (€/a)
- CO_2 emissions (t CO_2eq/a)
- Graphics (Sankey diagram energy flows, hourly load and load duration curve, flowchart energy system etc.)

4.2.3 Schematic and Detailed Design

To determine optimised network routes, tools such as QGIS[17] and FME[18] can be used to map energy demand, renewable energy sources, environmental influencing factors and existing infrastructure. QGIS is an open-source geographic information system to acquire, process and analyse data, it can also create maps and atlases to help design. FME is a data translation and transformation tool to solve data interoperability issues. In addition, it can strongly support geospatial data integration and transformation. For large, urban scale projects, it is often recommended to use FME for more efficient data processing and management.

GIS Mapping in QGIS

Input
- Low accuracy data: Energy demand benchmark or energy performance certificate
- High accuracy data: Energy demand from simulation or meter data
- GIS data from clients
- Open source GIS data

Output
- Network route (for network planning in FME or NetSim)
- Maps of constraints, network route, tiered load demand

As next step, applications such as NetSim[19] can be used to size networks and analyse their thermal and hydraulic performance. NetSim is a hydraulic modelling tool for district heating and cooling networks, it can be used to optimize pipe sizing and reduce pumping and energy costs. The important inputs and outputs are summarized below.

Heat network planning in NetSim

Input
- Nodes - Power (peak heat), return temperature, Z-height (elevation)
- Pipe type (DN size)
- Plant - Power (capacity), supply temperature, pressure

Output
- Node table
- Pipe table - Diameter (DN) and length (m)
- Maps of velocity (m/s), pressure gradient (Pa/m), pressure (kPa)
- Heat loss (kW)
- Differential pressure (kPa)
- Flow (kg/s)
- Pump power (kW)

17 QGIS is a free and open source cross-platform desktop geographic information system (GIS) application: https://qgis.org/en/site/index.html

18 FME: Feature Manipulation Engine: https://www.safe.com/

19 NetSim: Grid simulation system: https://www.vitec-energy.com/netsim-grid-simulation/

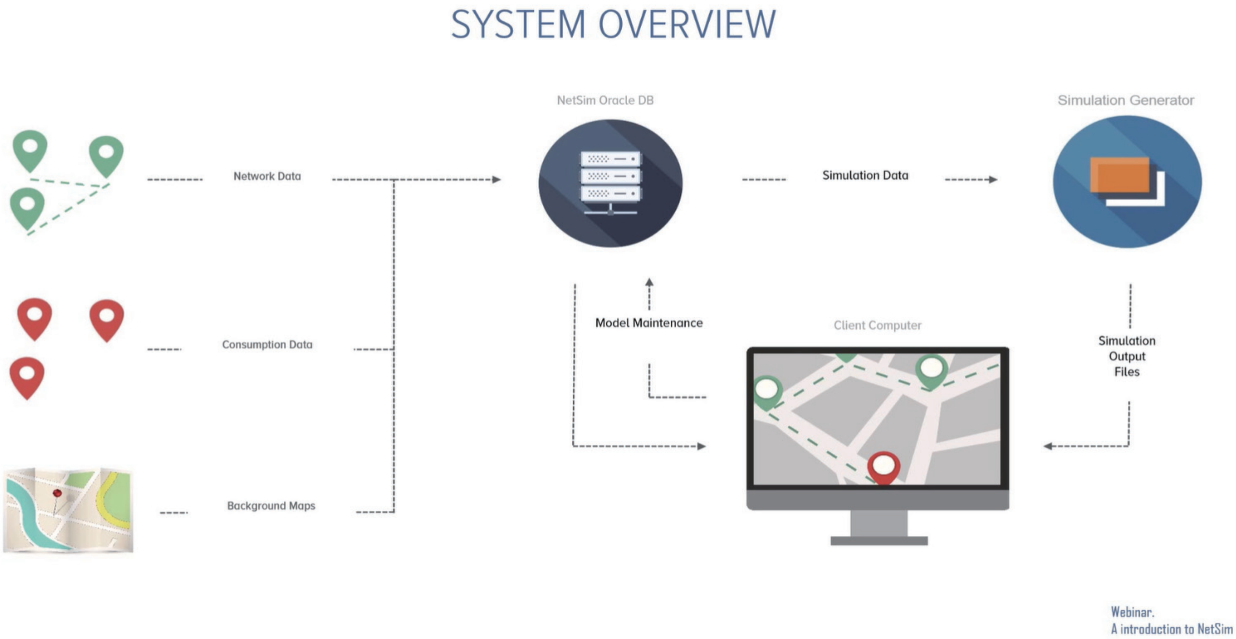


Figure 9 NetSim for heating and cooling network planning (source: Vitec Software, https://www.vitec-energy.com/netsim-grid-simulation/, accessed 07.12.2022)

Parallel to network planning, EnergyPro[20] can be used to simulate complex energy systems for detailed technical and financial analysis. It can offer more accurate results compared to Sympheny, as the calculations are made under due consideration to any conditions specified in the project. The important inputs and outputs are summarized below.

Energy centre plant sizing in EnergyPro

Input
- Archetype/exact data (survey/planning) of buildings
- Energy standard/benchmark (kWh/m²a)
- Available renewable energies (kW)
- Existing grid infrastructures
- Possible technical installations (supply, storage, transfer)

Output
- Design of technical systems (kW)
- Design of storage facilities (kWh)
- Graphic of energy balance
- Load curves
- Cost CAPEX and OPEX

4.2.4 Monitoring

As mentioned in previous chapter, data integration, processing and visualization throughout the project lifecycle are critical for large-scale energy projects. Therefore, the author has developed a workflow using FME and digital twin developed in-house. Figure 11 shows the basic function of FME- extract, transform and load data (ETL function) in new target location. With embedded transformers FME supports more than 450 spatial and tabular data types and formats, including CAD, GIS, XML, point cloud, raster data etc. In addition, FME offers interfaces to external tools such as excel and python, which makes it possible to build custom modelling suites in FME to perform calculations for different purposes.

FME uses entered data and uses various transformers to output data in the author's dataset for digital twin. FME

20 EnergyPRO is the leading software for modelling and analyzing complex energy projects with combined supply of electricity and thermal energy, please refers to website https://www.emd-international.com/energypro/

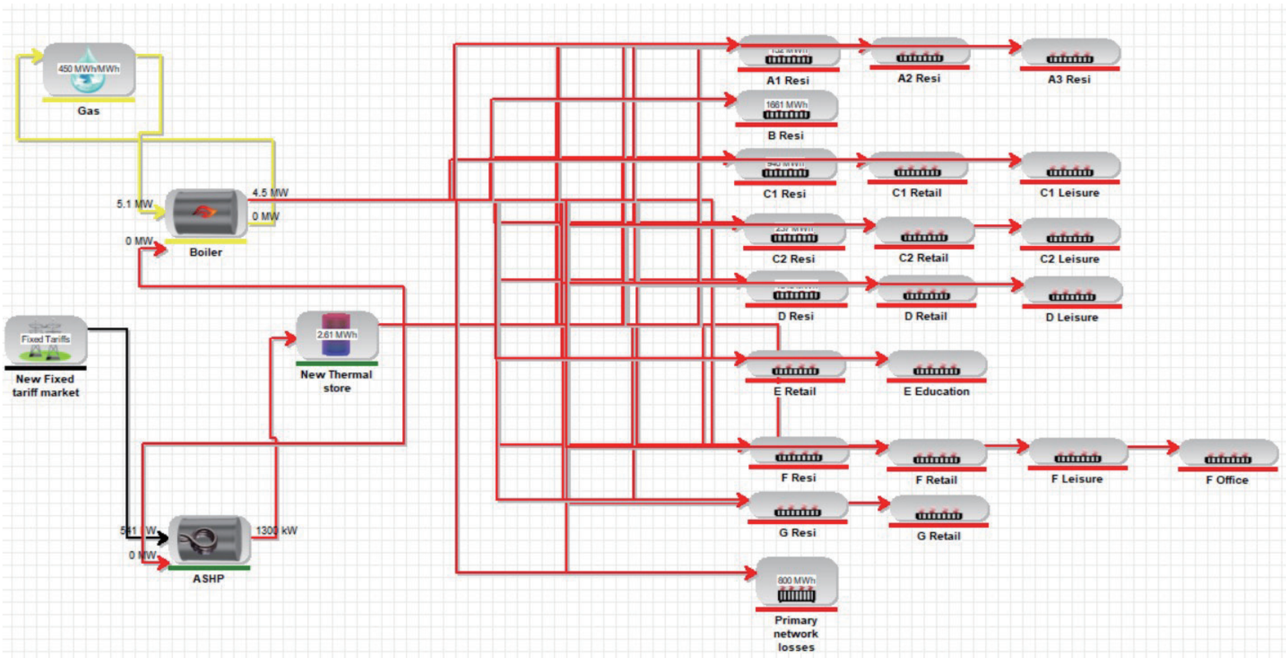


Figure 10 EnergyPro for detailed calculation of complex energy systems, EMD International A/S, energyPRO [Software] (Source: own illustration)

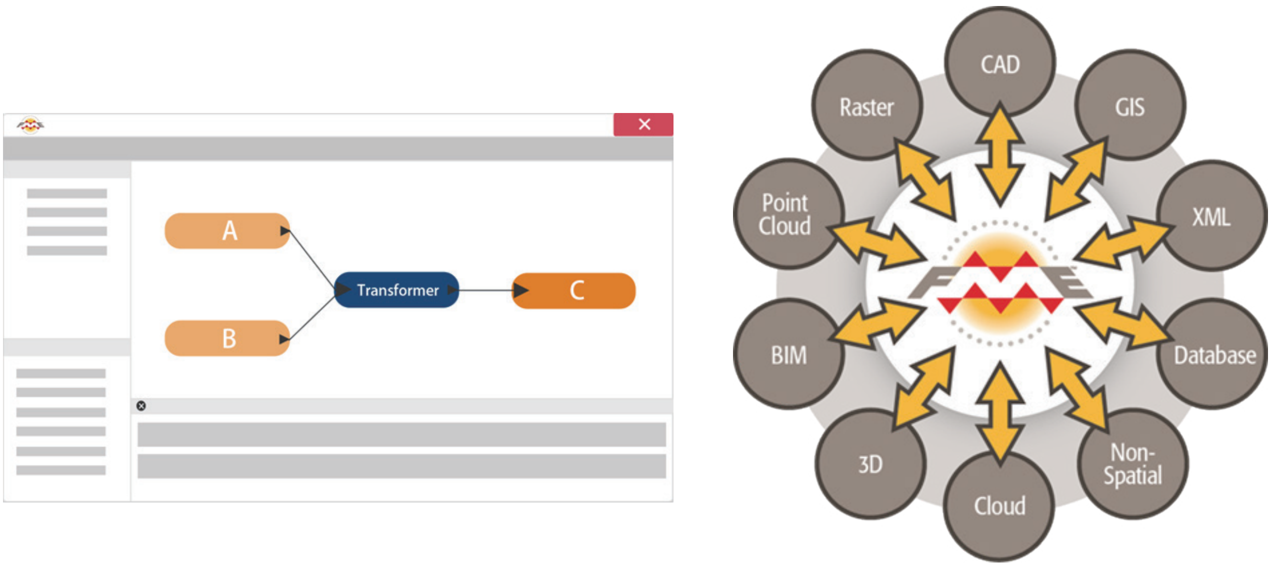


Figure 11 FME ETL function and supported data types (Source: SAFE Software, https://safe-software.gitbooks.io/fme-desktop-basic-training-2018/content/DesktopBasic1Basics/1.01.WhatIsFME.html, accessed 07.12.2022)

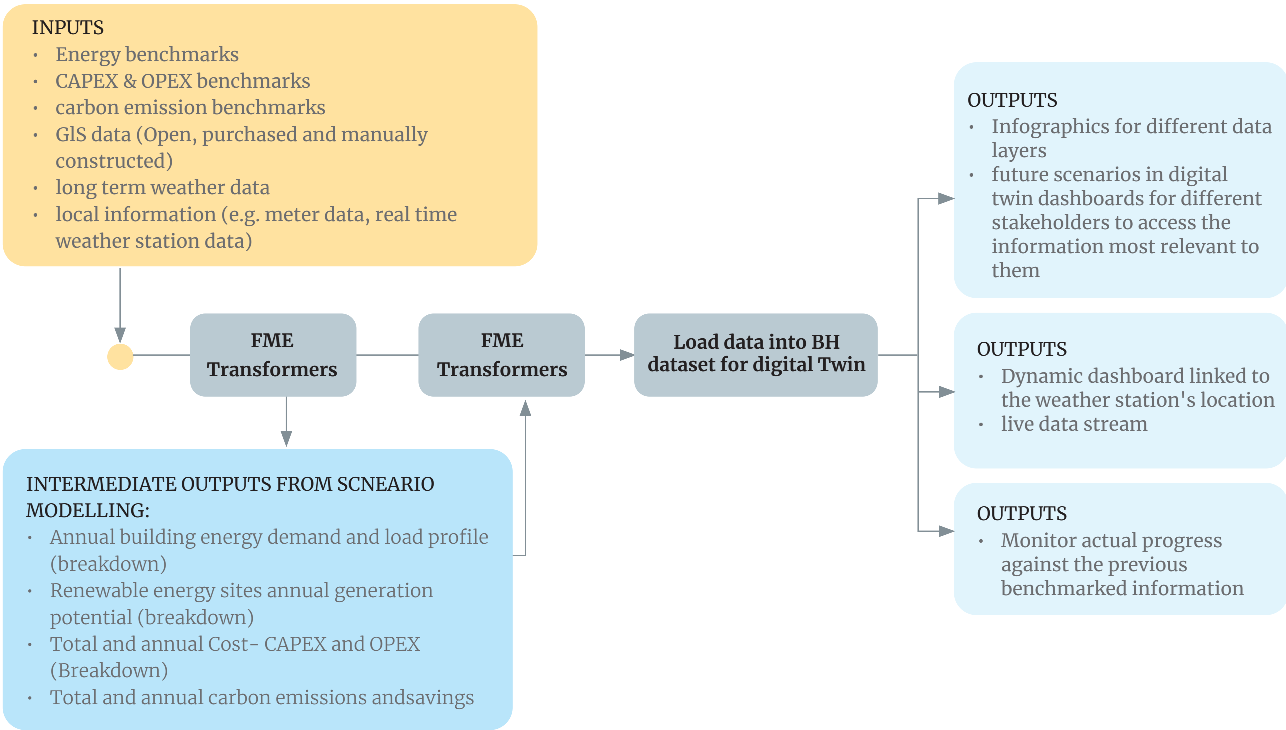


Figure 12 Inputs and outputs in FME and Buro Happold Digital Twin

allowed for maximum flexibility with data inputs including energy demand, building information, cost and financial inputs, GIS data etc. In Figure 12 typical inputs and outputs in FME and digital twin are presented.

There are different computer aided facility management (CAFM) tools, such as Planon[21] for energy and sustainability management in monitoring phase. Planon fetches data in operation phase including energy consumption, emissions and cost. It works with a platform that combines the benefits of an Integrated Workplace Management System (IWMS) with the capabilities of IoT in a smart building platform. The ability to connect all IoT devices and display them on a single dashboard opens new opportunities for data-driven insights to optimize building operations. Energy & Sustainability Management has been developed on the same platform, it can report and disclosure management of sustainability targets, realizing ESG ambitions in the built environment, and demonstrate reduction in carbon footprint.

4.3 Challenges and Opportunities

The previous section described an ideal planning process. Several factors, such as missing objectives, processes and communication gaps between designers eventually lead to failure to reach decarbonisation targets. Specific examples often found in practice are listed below:

- Inventory data is often only available on paper, consumption data is only available on annual electricity bills, BMS systems are not network-connected and become outdated.
- Duplication of work by different contractors. Manual data exchange between BIM models and simulation software. Information is lost between different project stages.
- Assumptions/benchmarks are used as inputs for dynamic energy demand during early design stages.
- Important decisions are based on incompleted or no data, missing opportunities to reduce emissions.
- Limited number of vendors on the market offering

21 Planon a tool to help collect, analyse, visualise and act on building data: https://planonsoftware.com/uk/resources/brochures/planon-energy-sustainability-management/

digital twin infrastructure for owners or project managers. High operating costs/ownership of the digital twin.

When looking at district scale further challenges are added to the above, such as:

- Defining the scale of investigation for local or regional renewable energies or waste heat potentials in the close proximity of the site
- Managing increased scope of tasks and actors as well as the related interfaces of the solutions
- Solutions for industrial parks or urban districts are often less replicable, it can be assumed this makes them less attractive for software development companies.

An ideal planning process for district energy design requires not only further development of digital tools to aid planning, but also the optimisation of cooperation between different participants in the project. Knowing about and using digital tools is an important step towards data-driven energy design. However, data management stands out as the most important role in integrated energy planning. Only by recognizing the importance of data quality and accessibility can planners, project operators, owners and users, utilities, public portals and other participants actively use tools and platforms for data collection and management.

The ideal planning process, supported by digital tools, should have the following characteristics:

- All the design inputs for feasibility studies at urban or neighbourhood scale are available from a **single source**. This should include access to as-built geometry, building components, systems, energy certificates, historical energy data, costs, etc.
- Seamless integration of design inputs, files and simulation results from all specialists into a platform, which acts as a single source of truth. Support for **lossless information transfer** between different design phases through to Facility Management and user interaction.
- Systems exist to **transfer knowledge** about performance gaps from completed projects on other projects.
- Responsible entity for data management for the whole lifecycle from early planning stage to monitoring of the operation.

Figure 13 Planon integrated solution on a comprehensive and open platform (Source: Planon, https://planonsoftware.com/us/resources/brochures/planon-energy-sustainability-management/, accessed: 07.12.2022)

5 Learnings and workshop outcomes

The project included two workshops with representatives from research and industry. The first workshop was held in German and evolved around the content shown in this report. The learnings were used to enhance the presentation content for the second workshop, which was held in Chinese and English. The presentations alternated between content shown in this report and presentations by Chinese participants showing digital building twins and planning tools.

5.1 Outcomes from the first workshop

The goal of the first workshop was to support this venture with an overview of digital tools and offer an optimized planning process. Dena hosted Buro Happold on the 26 October 2022 to present first findings to German experts from various institutes/consulting companies (Fraunhofer, Intep) and Universities (KIT, RWTH, TU-Darmstadt). The discussion provided useful feedback to the organisers, with the key points summarised below.

5.1.1 Observations

The first observation was that no package stood out as offering a solution for the entire design process. There are far more software packages out there than could be reviewed, but even given the selected corresponding to each stage of the design process, many packages were new to the domain experts in the meeting. This highlights the importance of such comparative studies and of national and international collaboration since experts typically focus more on their respective domains rather than the entire design/planning chain and ecosystem, and the cost of testing and learning new solutions is prohibitive.

The second observation was the challenge of transferring information within and between disciplines and the respective tools, for example between architectural and building energy models, building energy and district supply models, etc. The industry's response in the last few decades has focused on Building Information Modelling (BIM) as an alternate approach to 2D and 3D CAD, which together with exchangeable data formats such as gbXML and ifc has attempted to include semantic information in building elements. This approach is useful for later, detailed design, however it does not meet the needs of earlier design stages where design uncertainty is still high, and many iterations are necessary. The current generation of tools is getting better at modelling different scenarios, but the vision of an integrated, seamless workflow still seems out of reach for the time being.

The workshop participants highlighted another challenge to "single package" approach covering all stakeholders and design stages: discipline-specific liabilities. This is not really an issue in today's fragmented industry where a lot of work is duplicated, but in a perfectly streamlined scenario, work done by certain experts may need to be ring-fenced from the rest of the process to avoid accidental modification by other planners and stakeholders.

5.1.2 Process recommendations

The challenge of information management at the earliest design stages can be overcome by setting up process requirements and appointing a technical information manager who ensures that design objectives (e.g. emissions targets) are clearly communicated, all inputs and outputs to the design process are documented centrally, avoiding information gaps, duplicating work and introducing errors. This role could also include facilitating information transfer between the different disciplines by requiring the use of certain formats or packages for the project.

The technical information manager should also bear the "data estate chasm", i.e. the contractual gap between the designers and builders and operating team where most design information gets lost. All the design inputs (e.g. Weather data, building use assumptions, material suppliers, simulation models, etc.) need to be available to all the planners, facility managers and tenants on a project.

5.1.3 Open Questions

The biggest challenge in decarbonising districts is the coordination effort needed between all parties, both from an organisational and technical perspective. The system boundary of an energy district depends on factors such as land ownership, laws governing energy providers, land use, etc. It is project specific and should be defined during the pre-concept stage. Since the idealised process was based on experience on past projects, some important players may have been omitted.

The next decade will see a surge in electrification of mobility, which will inevitably connect to district networks and the grid. This is a new use case and will change how energy is managed in buildings. However, none of the tools investigated so far seemed able to consider this scenario. Given the electrification rate in the mobility sector compared to the speed of the construction industry, it is possible that the former will be the first to offer tooling to model and manage building and mobility energy simultaneously.

5.2 Outcomes from the second workshop

A second workshop was held on 22 November 2022, with the participation of Chinese experts from various fields: design and research institutes, e.g. State Grid (Suzhou) Research Center, China academy of building research (CABR), Tsinghua architectural design and research institute (THAD), environmental consulting companies such as CECEP, representative of universities Sichuan University, software developers as Lubansoft, and technical equipment manufacturers (e.g. SHAANGU).

5.2.1 Observations

Industrial parks account for a large proportion of energy use and related emissions, with industrial processes using far more energy than the buildings themselves. In these cases, process energy must be included within the system boundary. Some of the software packages presented in this report would be able to include process energy, however, this aspect is not directly included in the scope of "building emissions" used in this report. Yet, the importance highlights the need to include emissions from industrial processes in achieving decarbonisation goals.

Research institutes in China have already developed digital tools to support integrated energy system design, such as the Integrated Energy System Analysis Cloud Platform - planning and optimisation tool from state grid (Suzhou). Based on the speech and display shown in the workshop, this tool has a pre-set comparison of expenses vs emissions, as found in Sympheny and CEA Toolbox. Unfortunately, this platform is not commercially available at time of writing and could therefore not be investigated in detail.

Participants from CABR with experience creating digital twins of campus energy system also shared some of the difficulties they encountered in the design: incomplete basic data and discrepancies between design and construction phases. This is a universal problem in the industry which a new generation of digitized site-management and QA technology can help address.

5.2.2 Process recommendations

Process energy needs to be included within the system boundary during pre-concept stage, so that all energy sources are addressed and potential economies of scale unlocked. The contractual implications are country specific and merit their own study to determine whether the problem is just technical or whether additional legal reforms in energy policy and planning law are required for collaboration between district and factory operators. This could lead to a rulebook for industrial parks with emissions targets and process guidelines for achieving them.

The pilot projects presented in the workshop showed promising applications for live data for performance monitoring, exposing emissions data and as input to the design and upgrade of districts and industrial parks. Still, the data which these tools rely on often not available on projects, so a lot of work is needed to generate this information and to make decisions based on less information.

5.3 Desired attributes of low-carbon design tools

A few software features stood out as very desirable in design tools for low carbon districts.

- Multi-objective optimization of cost and emissions (puts decarbonisation in focus)
- Easy Access to inputs and outputs via an API (important for Quality Assurance and sharing results)

- Good dashboarding and customizable reporting (better quality assurance and helps more technical users explain the analysis to decision makers)

The same features apply to monitoring tools, including dashboards and digital twins, which have an important role in the ecosystem. Some of the examples had an interactive 3D user interface, however this is just a front-end feature and does not automatically define a tool as being a digital twin.

Further features of design tools for low carbon districts included the following:

- Account for uncertainty (e.g. weather, energy prices)
- Develop demand profile estimation based on simple building features
- Share certain data between building and urban scale
- Model multiple scenarios for use and financial conditions
- Integrated cost calculations are better for decision making.
- Free and open source
- Big user base, well documented online
- Inputs and outputs accessible via API
- Language and future availability are important for slower, bigger projects
- A platform, which interfaces with all the specialist processes and is a single source of truth for the lifecycle of the project
- Make the information accessible to stakeholders with different backgrounds and technical ability.

5.3.1 Advantages of a platform

As part of the research process, FME was identified providing a flexible platform, which allows the integration of various data points and can effectively manage enormous amounts of data in an urban scale project. Furthermore, FME allows linking to various tools (e.g. Excel and Python) and can embed them as built-in models, which extends its calculation capability. Due to its powerful data processing capabilities and extensibility through custom and project specific features, FME offers the following advantages:

- Integration of data from various simulation tools and geodatabases
- Automatic data translation with embedded transformers
- Easy extraction of data to perform analysis at different levels of detail
- Transparent process and absolute control over all data streams
- Develop different built-in models in parallel and enable to link them in a central structure
- Potential to better manage liability, individual specialists can still use their tools but feed into a central repository
- Validation of input data to improve data quality and increase modelling resilience

Meanwhile, the following perspectives should be considered when using FME:

- Requires good data management and structure to be effective
- As with most models, it is most effective if there is a separate owner for each model. However, this will increase the complexity of the whole system and dependency on people working to certain formats/ output parameters. FME has the ability to easily mesh models to help overcome this problem
- In FME, vector data is better suited for spatial analysis than raster data, which often requires pre-processing in GIS.

5.4 A pilot project as showcase

After the intensive studies on energy planning tools and the findings gained from two workshops with German and Chinese Experts, the common understanding of the participants was that organising a pilot project to showcase the optimization of this planning process would be a good opportunity to test the findings in practice. The pilot should be a development of an integrated concept of a city quarter or district with international and local experts. The objectives for such an integrated project are to identify digital planning and software tools for the different development stages and to achieve climate neutrality, based on a standardized approach.

With the ideal combination of software tools, all project team members could provide their contribution to complete the project in the best possible way within time and budget.

If all selected software tools and their output data can be easily integrated or linked in a platform, it can greatly facilitate data management and reduce data loss. With the data-consistent project flow, the project can be transferred to the commissioning phase and move easily into the operational phase. The more precise and comprehensive the data can be transferred from the planning phase to the operational phase, the more precisely this data can be used in operation, e.g. for data and energy management, so that the optimum can be extracted from the properties.

6 Outlook

The applied investigation and expert exchanges show that there is no silver bullet to address all application cases in the context of urban development and the planning or industrial sites or districts, although a large number of specific software solutions is available in the market. The main discussion points and findings can be summarised in four categories. First of all, looking at different tools and data handling starts in the early stages of a project, therefore the design process is an important phase to set the requirements and start building up consistent processes. Data management is an important activity during all project phases, especially building up and maintaining a consistent set of data is key to avoid loss of information in the different phases. A number of aspects have been identified during the workshops regarding the needs for tool development and subsequently standards to provide the necessary interfaces. Finally, a future vision addressing many of the open issues is the development of urban digital twins. While in comparison to industry, the planning sector is still in the early phases of the development, digital twins are promising solutions especially for the planning and possibly operation of industrial parks.

6.1 Design Process

The applied projects showed the relevance to include the process of data management in the early design phases. It is mandatory to develop a data strategy early on in the project to avoid inconsistent data infrastructures, loss of data and parallel data collection processes. Therefore, also stakeholders and necessary services in later project phases must be identified in order to guarantee the appropriate information for the whole project. This planning would greatly benefit from standard data conventions and standardised processes for data collection. In an ideal way, simulation and monitoring would be understood as a continuous process throughout the project lifecycle based on consistent data sets with increasing level of detail as more information is gathered.

Today, still a number of difficulties are encountered in the design of district scale energy systems, due to e.g. incompleted basic data, discrepancy between design and construction phases.

6.2 Data management

Exchanging data across tools is key, especially connecting demand- and supply-focused tools. An important challenge therefore is to avoid information loss at interfaces between stakeholders and their respective tools. On the other hand, global data sources such as weather data need to be well documented but can be shared in the whole project group. Finally, especially with regard to quality control and monitoring, more live data needs to be collected and used for performance monitoring,

The investigation of planning tasks also showed that the software used by different experts need to be separated with a clear interface because of discipline specific needs and responsibilities in the project. Therefore, the multitude of applications is corresponding to the different use cases connected to different services and tasks.

As shown in Figure 6 a clear distinction can be made between data management and applications using and processing the data. The discussions in the workshops as well as findings in the project point out that data management should be a continuous process throughout the projects phases. Applications need to be specialised but can interface with a harmonised data layer. For this however, conventions for the interfaces as well as for the data objects need to be harmonised.

In advanced projects, data is stored in an urban data platform sometimes also referred to as an urban data hub. One of the German cities currently building up such an urban data hub is the city of Hamburg, using a 3D data

22 Hamburg Urban Data Hub: https://www.hamburg.de/bsw/urban-data-hub/

model of the city's building stock, mobility data and a wide range of further sources[22]. The data collected in this way can be used by both, experts and citizens. All actors involved can thus make faster, better and rethought decisions.

6.3 Standards as a Basis for Tool Development

To support integrated energy system design, there is a large community of research and planning institutes worldwide that have developed a range of digital applications. Examples have been presented in the two workshop session such as the Integrated Energy System Analysis Cloud Platform, a planning and optimisation solution from State Grid (Suzhou). Based on the speech and display shown, some of the features of this tool such as the embedded comparison of expenses versus emissions can be found in other applications such as Sympheny and the CEA Toolbox. The multitude of solutions shows the overall need for the planning of industrial districts. On the other hand, the lack of standards reduces the opportunity to develop interoperable tools. The definition of standards for e.g. data models can be seen as a prerequisite for effective and collaborative tool development in order to make solutions available that are comparable and can exchange data throughout the different project stages.

6.4 Digital Twins

A more advanced development of integrated simulation, monitoring and operation of urban or district scale projects are **urban digital twins**. Digital twins are digital representations of parts of the real world. They describe both physical objects and non-physical things such as services. A digital twin can describe existing or planned objects and processes.

The central motivation for the realization of digital twins is to enable a comprehensive exchange of information. Digital twins, which are often used in manufacturing, also make it possible to plan the production of a product virtually. Digital twins represent different information in a uniform format and include algorithms that accurately describe their real-world counterpart. These are often simulation models that simulate functional or physical properties of the digital twin. If these simulation models are executed with real data, then the digital twin ideally behaves exactly like its real counterpart. Complex systems can be put into virtual operation before they are actually completed.

While basic or enriched digital twins represent the real world, enhanced digital twins can become part of an interoperable cyber-physical system[23].

Digital twins have been developed and applied in various industrial sectors. However, so far there is no common view or approach for a digital twin of district or municipality. Currently standardization activities on the topic of digital twins are being initiated or are already ongoing at European and international level.

In order to develop and harmonise the approach towards digital twins for cities and districts, more than 30 organizations, including 14 municipalities and municipal associations, joined the development of DIN SPEC 91607[24] and will work together over the next 20 months to present a digital twin for cities and municipalities. The initiative is partly financed by the Federal Ministry of Housing, Urban Development and Building (BMWSB) project "Connected Urban Twins" (CUT[25]). The objective is the creation of a (national) standard for transferring the concept of digital twins to urban space, by presenting and describing application scenarios, data access and visualization methods, as well as the use of available standards.

6.5 Next Steps

Both workshops clearly showed the interest of the participants but also the value of the exchange. Dedicated workshops can add value to the discussion about applied solutions for practitioners but also for tool developer. Sometime both functions fall together as planners add

23 Definition according to the German Society for Informatics, https://gi.de/

24 DIN SPEC 91607 Digital twin for cities and communities: https://www.din.de/de/wdc-beuth:din21:347212214

25 CUT: Connected Urban Twins: https://connectedurbantwins.de/

functionalities to the existing set of tools. Therefore, regular exchanges and active cooperation with synergy effects between national and international experts are necessary and helpful. The overall approach confirms the relevance of the topic. Examples of actual planning processes were shown to illustrate the combined use of multiple tools. An important next step lies in the development of consistent use cases for the integrated planning of districts. A structure to better categorise and delaminate use cases is presented in this report (Figure 5).

Structured use cases can help to translate actual planning tasks into the functional requirement of software tools and inform the development of standard data models. This provides a common language for planners and solution developers.

While the focus of the work presented in this report lies in the planning of climate neutral districts, future developments point to the role of urban digital twins. In comparison to planning tasks, the possible bi-directional communication between model and reality would allow for a consistent data model throughout the planning process that can also serve as basis for the operation and monitoring of real-life installations in a cyber-physical system.

As the further development described above would require both real life planning as well as IT development, a structured discussion bringing together communities/cities, planners and data scientists or software developers would be necessary to define future development opportunities such as pilot projects in which development projects would be accompanied by dedicated development teams.

Source: 699pic.com

Appendix 1

Matrix of software tools

						Building Energy Modelling				District Energy Planning Tools									Data Integration Tools				Operation Tools
		Filter 1	Filter 2	Filter 3	Filter 4	TRNSYS	Energyplus	IDA ICE	IES VE	CEA Toolbox	Sympheny	District Energy Concept Adviser	OEMOF	TIMES	HKE SIM (dymola modelica)	EnergyPro	NetSim	THERMOS	BuroHappold Digital Twin	FME	QGIS	ArcGIS	Planon
Goal	Target or purpose of using the software	Planning Energy supply concept	-	-	-	Planning Energy supply concept, Building Simulation	Building Simulation	Building Simulation	Building Simulation	Energy supply concept, Planning	Planning Energy supply concept	Planning Energy supply concept	Planning Energy supply concept	Planning Energy supply concepte	Building energy modelling, including physics and system modelling, Optimize and design economic solutions with guaranteed energy consumption	software for modelling and analyzing complex energy projects	Hydraulic modelling tool for district energy networks.	thermal energy network planning software	Data management and visualizing	Geospatial data processing, translation, integration	Geospatial data visualization and analysis	Geospatial data management, visualization and analysis	Convey all data relevant for building operation; maintenance and building management
	Application areas (if it´s limited by some conditions like using local database or standards)	global	-	-	-	global, research	global	lokal	local	Europe	global	lokal	global	global	Buildings, Districts	global	global	global	global	global	global	global	global
	Calculation methodology (integrated standards/ guidelines)	Integrated norms	-	-	-	ASHRAE Standard 55-2013, DIN 13779, VDI 2078 and SIA 2024	LEED, ASHRAE	"Integrated norms: DIN 4108-2:2013-2, Tageslicht, Ashrae 90.1 (LEED&BREEAM)"	"Integrated norms: ASHRAE 90.1, CIBSE, IECC, Tageslicht"	"ISO Standard for Simulation (Energy load simulation); SIA for building properties and control"	no integrated standards/ guidlines	"Integrated norms: DIN 18599, 2016"			Thermodynamic processes according to H/X Module	no integrated standards/ guidlines	no integrated standards/ guidlines	no integrated standards/ guidlines	no integrated standards/ guidlines	no integrated standards/ guidlines	no integrated standards/ guidlines	no integrated standards/ guidlines	Integrated norms: ASHRAE, DIN, SIA, Ö-Norm
Resolution	spacial resolution (region, district, building level ...)	District	City	--	--	Building	Building	Building, (District unter Entwicklung)	building	District, City, Building	Building, District, City, Region	Building, District	Building, District, City, Region	World, Country, Region	Building, District, City, Region	Building, District, City, Region	District, City, Region	District, City, Region	Building, District, City, Region	Building, District, City, Region	Building, District, City, Region	Building, District, City, Region	from building to region
	temporal resolution (yearly, monthly or hourly ...)	hourly	annual	--	--	annual, monthly, daily, hourly, sub-hourly	annual, monthly, daily, hourly, sub-hourly	annual, monthly, hourly, sub-hourly	annual, monthly, hourly, sub-hourly	annual, monthly, hourly	annual, monthly, hourly	annual, monthly	annual, monthly, daily, hourly, sub-hourly	annual	hourly	annual, monthly, daily, hourly	annual, hourly	annual, daily	annual, monthly, daily, hourly, sub-hourly	annual, monthly, daily, hourly, sub-hourly	annual, monthly, daily, hourly, sub-hourly	annual, monthly, daily, hourly, sub-hourly	realtime

Method	Simulation approach/ algorithm	--	--	--	--	Fortran compiler with a multizone builder on top	Simulation Engine	Equation-Based Solver	Dynamic simulation	Master-slave Routine Evolutionary Algorithm	MILP	Equation-based	MILP	MILP	Equation-based Model	MILP	MILP	MILP	n.a.	depends on integrated programming and calculation tools (python, spreadsheet ...)	n.a.	n.a.	"IoT capable Planon-Platform"
	Optimization method (if applicable)	Multiple objective optimization	--	--	--	n.a.	n.a.	Automoo (built-in optimizer chooses the best algorithm)	Parametric tool available as an extra	Multiple objective optimization	Multiple objective optimization	n.a.	Linear optimization	Multiple objective optimization using linear programming		Multiple objective optimization	Multiple objective optimization	Multiple objective optimization	n.a.	variable, depending on optimization objectives	n.a.	n.a.	optimazition possible
	Optimization objectives (if applicable)	Emission	Comfort	Costs	--	n.a.	n.a.	Emission, Costs, Comfort	Emission, Costs, Comfort	Costs, Emission	Emission, Costs	n.a.	Costs	Costs, Emissionen. "Cheapest end-use energy service while also meeting emissions reduction and renewables penetration constraints"	Emission, Costs, Comfort	Emission, Costs		felxible, chosen by user, such as cost, emission	n.a.	Emission, Costs, Comfort, end use energy, Primärenergie ... (variable, depending on needs)	n.a.	n.a.	IoT-devices, Sensors, Smart Technologies
Interfaces	Data interfaces to other software tools, databases and data sources (e.g. operational data)	tabular data	--	--	--	tabular data, spatial data (Sketchup, Rhino+Grasshopper)	Energyplus is just a simulation engine designed to interface with a separate graphical interface. Two popular interfaces are OpenStudio and Ladybug Tools.	spatial data (cad, sketchup, .dwd Wetterdateien, ifc (begrenzt))	tabular data (Input and Output in gbXML), spatial data (3D Model Import durch Revit/SketchUp Plug-in and über gbXML, veXML or IFC, 2D CAD Import über DXF), anders (integrierte Tools z.B. One Click LCA, LEED - highly dependant on quality of input geometry)	tabular data (csv), spatial data (shapefile)	tabular data (csv input/ output)	closed system	tabular data (csv input/ output)	Veda 2.0, spreadsheets	others (EnergyPlus)	tabular data (csv, XML)	tabular data (csv, XML, database from network information systems on the market), spatial data (DXF/DWG, Raster)	tabular data (csv, XML), spatial data (GIS Geojson, shapefile,LIDAR data)	spatial data (Geospatial databases)	tabular data (csv, XML, database, Non-spatial ...), spatial data (GIS, CAD, Raster, Point cloud, BIM, 3D ...) over 400 formats	spatial data (Geospatial databases)	spatial data (Geospatial databases)	Tailor-Made Software Interface; Data Exchange protocol; Tests; Accepts alphanumeric (tabular) data from other systems over the Enterprise Talk interface; graphical data (DWG, DXF) can be imported
	Consideration of digital building models(BIM)	Yes	Yes	--	--	No	No	Yes	Yes, Export geometry and material from Revit in gbXML file (dependant on quality of input geometry)	No	No	No	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes, Bidirectional standard connector to Autodesk Revit (BIM) for BI-tools such as MS PowerBuilder

	in which planning phases will it be used	Project development (LPH0)	Concept Design (LPH1-2)	Planning (LPH3-5)	--	Project development (LPH0), Concept Design (LPH1-2), Planning (LPH3-5)	Project development (LPH0), Concept Design (LPH1-2), Planning (LPH3-5)	Project development (LPH0), Concept Design (LPH1-2), Planning (LPH3-5)	Concept Design (LPH1-2), Planning (LPH3-5), Operation	Project development (LPH0), Concept Design (LPH1-2)	Project development (LPH0), Concept Design (LPH1-2)	Project development (LPH0), Concept Design (LPH1-2)	Project development (LPH0), Concept Design (LPH1-2)	Project development (LPH0)	Concept Design (LPH1-2), Planning (LPH3-5), Operation	Concept Design (LPH1-2), Planning (LPH3-5)	Concept Design (LPH1-2), Planning (LPH3-5)	Concept Design (LPH1-2)	Project development (LPH0), Concept Design (LPH1-2), Planning (LPH3-5), Monitoring/ Operation	Project development (LPH0), Concept Design (LPH1-2), Planning (LPH3-5), Monitoring/ Operation	Project development (LPH0), Concept Design (LPH1-2), Planning (LPH3-5), Monitoring/ Operation	Project development (LPH0), Concept Design (LPH1-2), Planning (LPH3-5), Monitoring/ Operation	LP8 Commissioning, LP9 Documentation, Monitoring/ Operation
Scope	Carbon footprint calculation scopes that are considered (LCA-materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling)	Supply	Use	End of life	Offsets outside the system boundary	n.a.	n.a.	Use (Manual factor input)	Use	Use, embodied carbon also possible in the future	Use, embodied carbon also possible in the future	Use	Use	Use	Use	Use	n.a.	**Use**	n.a.	Supply, Use, End of life, Offsets outside the system boundary	n.a.	n.a.	Data
	Sector coupling can be modeled (heat, power, gas, transport)	Heat	Electricity	Gas	Transport	Heat, Cooling, Electricity, Gas	Heat, Cooling, Electricity, Gas	Heat, Cooling, Electricity, Gas	Heat, Cooling, Electricity, Gas	Heat, Cooling, Electricity, Gas	Heat, Cooling, Electricity, Gas	Heat, Cooling, Electricity, Gas	Heat, Cooling, Electricity, Gas	n.a.	Heat, Cooling, Electricity, Gas	Heat, Cooling, Electricity, Gas	n.a.	n.a.	n.a.	Heat, Cooling, Electricity, Gas, Transport	n.a.	n.a.	IoT and Sensors
	Transparency of the simulation system (open source or closed source)	open source	--	--	--	Source code available upon purchase, except for the multizone building model	Open source	open-source objects, Closed-source solver	open source (calculation methodology open, but software closed)	Open source	Closed source	Closed source	Open Source	Open but relies on closed-source packages (GAMS, VEDA)	closed source	closed source	closed source	Open source	closed source	closed source (software), data open	open source	closed source	closed source
Transparency	Accessing the input data for validation (very good - absolute control; good - all input and output data is accessible; Fair - limited access; poor - no access)	very good	good	--	--	Fair: Possible to import results into excel, limited examples of this working	very good	Fair: Limited access to data, Inputs and Outputs can be exported to Excel but the formatting is not intuitive. Good access to all output data in .csv vormat, but some post-processing necessary	Fair: Limited access to data, Output in DXF, PDF, Excel, jpeg...	Good: Input and Output data is accessible in Excel	Good: Input and Output data is accessible in Excel	Fair: Limited access to data	"very good Complete control"	very good	very good, Complete control	Good	Good	very good	very good	very good	very good	very good	very good
	Energy calculation boundary (end use energy, primary energy, tenant energy/energy consumed by users)	Tenant Energy	end use energy	--	--	end use energy	end use energy	end use energy (Heating, Domestic Hot Water, Cooling, Lighting, Ventilation, Auxiliary energy), Tenant Energy	end use energy (Heating, Domestic Hot Water, Cooling, Lighting, Ventilation, Auxiliary energy), Tenant Energy	end use energy (Heating, Domestic Hot Water, Cooling, Electricity)	end use energy (Heating, Domestic Hot Water, Cooling, Electricity)	end use energy (Heating, Domestic Hot Water, Cooling, Lighting, Ventilation, Auxiliary energy), Tenant Energy		energy demand is an input, the model focuses on primary supply	end use energy (Heating, Domestic Hot Water, Cooling, Lighting, Ventilation, Auxiliary energy), Tenant Energy	end use energy (Heating, Domestic Hot Water, Cooling, Lighting, Ventilation, Auxiliary energy), Tenant Energy	n.a.	n.a.	n.a.	end use energy (Heating, Domestic Hot Water, Cooling, Lighting, Ventilation, Auxiliary energy), Tenant Energy	n.a.	n.a.	end use energy (Heating, Domestic Hot Water, Cooling, Lighting, Ventilation, Auxiliary energy), Tenant Energy

Energy Sources	Integrated geographic or environmental data	built-in Datasets	--	--	--	built-in dataset: weather data	n.a.	built-in datasets: Weather data and norms for some European countries	built-in datasets (global weather data)	built-in Datasets	built-in datasets (Solar irradiation for Switzerland, otherwise manual input)	built-in datasets - German Weather Data, Solar energy potential	None	built-in datasets: technologies from EPA-ORD, US DOE, US MARKAL, and others	built-in datasets - Weather data	has built-in datasets	built-in Datasets	built-in Datasets	"built-in datasets - google map layer, GIS layer, more layers possible"	None	built-in datasets (open source e.g. OS Map, pug-ins with remote sensor data, environmental data)	built-in datasets (own library)	None
	Ability to calculate energy from different sources (on site or grid connected)	Network-connected energy sources	On-Site energy sources	--	--	Network-connected energy sources, On-Site energy sources	Network-connected energy sources	Network-connected energy sources, On-Site energy sources	Network-connected energy sources, On-Site energy sources	Network-connected energy sources, On-Site energy sources	Network-connected energy sources, On-Site energy sources	Network-connected energy sources, On-Site energy sources	None	This is designed to calculate efficient supply systems (grid scale)	Heat, Cooling, Electricity and Wasser	Network-connected energy sources, On-Site energy sources	n.a.	n.a.	n.a.	Network-connected energy sources, On-Site energy sources	Network-connected energy sources, On-Site energy sources (spreadsheet calculation)	Network-connected energy sources, On-Site energy sources (spreadsheet calculation)	None
Technologies	Conversion technologies considered in sofrware (traditional or new technologies e.g. fuel cell)	Conventional Technology	New Technology	--	--	Conventional Technology	Conventional Technology	Conventional Technology	Conventional Technology	Conventional Technology, New Technology	Conventional Technology, New Technology	Conventional Technology	All	Conventional Technology, new technology	Heat, Cooling, Electricity and Wasser	Conventional Technology, New Technology	n.a.	Conventional Technology	n.a.	Conventional Technology, New Technology	Conventional Technology, New Technology (spreadsheet calculation)	Conventional Technology, New Technology (spreadsheet calculation)	n.a.
	Network modelling (e.g. heat and power network)	Heat Networks	Electricity Networks	--	--	None	None	None	None	Heat Networks, Electricity Networks	None	None	None	None (not for design purposes)		None	Heat Networks	Heat Networks	n.a.	Heat Networks, Electricity Networks	Heat Networks, Electricity Networks (spreadsheet calculation)	Heat Networks, Electricity Networks (spreadsheet calculation)	n.a.
	Storage modelling (e.g. model different energy storage technologies, short-term or long-term storages)	Thermal Storage	Electric Storage	Building Scale (short term)	District Scale (long term)	Thermal Storage, Electric Storage, Building Scale (short term)	Thermal Storage, Electric Storage, Building Scale (short term)	Thermal Storage, Electric Storage, Building Scale (short term)	Thermal Storage, Electric Storage, Building Scale (short term)	Thermal Storage, Electric Storage, Building Scale (short term)	Thermal Storage, Electric Storage, Building Scale (short term), District Scale (long term)	Thermal Storage, Electric Storage, Building Scale (short term)	Thermal Storage, Electric Storage, Building Scale (short term), District Scale (long term)	on the roadmap		Thermal Storage, Electric Storage, Building Scale (short term), District Scale (long term)	n.a.	Thermal Storage	n.a.	Thermal Storage, Electric Storage, Building Scale (short term), District Scale (long term)	Thermal Storage, Electric Storage, Building Scale (short term), District Scale (long term) (spreadsheet calculation)	Thermal Storage, Electric Storage, Building Scale (short term), District Scale (long term) (spreadsheet calculation)	n.a.
Economic Feasibility	Integrated cost-efficiency calculation	Yes	--	--	--	No	No	No	Yes	Yes	Yes	Yes	Yes	yes		Yes	Yes	Yes	No	No (possible to add functions)	No	No	Yes
	CAPEX oder OPEX	CAPEX	OPEX	--	--	No	No	OPEX	OPEX	CAPEX, OPEX	CAPEX, OPEX	CAPEX, OPEX	CAPEX, OPEX	CAPEX, OPEX		CAPEX, OPEX	CAPEX, OPEX	CAPEX, OPEX	No	No (possible to add functions)	No	No	CAPEX, OPEX
	linear or dynamic (CAPEX)	linear	--	--	--	No	No	Linear	Linear	Linear, dynamic	Linear	Linear	linear	Linear		linear	linear	linear	No	No (possible to add functions)	No	No	linear
	Static or forecast (CAPEX + OPEX)	forecast	--	--	--	No	No	static	static	static	static	static	static	forecast possible	forecast	forecast	static	static	No	No (possible to add functions)	No	No	static

User-Friendliness	Installation requirements	--	--	--	--		free download and Local installation	Netz-lizens möglich	Standalone or network license	free download and Local installation	Cloud-based	free download and Local installation	free download and Local installation, complex to install	local installation		Local installation	local server installation	web based	web-based	Local installation	Local installation	Local installation	project based
	Advantages compared to other softwares	--	--	--	--		Free, Widely adopted, open source, State financed	Precise, open-source, very flexible	Precise, open-source, very flexible and Expandable, very flexible	open-source, Free Software, Precise technology description, accesses various databases, interface, database (min. Input), Ability to model buildings spatially, Simulation and Optimisation of heat networks	Fast, well maintained, good support	Fast, based on German norms and energy standards	open-source, Free Software, Control, Possible to modify	Well documented and several example usecases available. Specialised in scenario analysis for strategic planning. Global user base	Integrated Analysis of Buildings, Production, Ventilation systems, Energy Systems and Flow Rates.	Precise Simulation Results, System size optimisation, various constraints (Peak Load Electricity Cost, constrained Gas- and Electricity supply)	Precise Simulation Results, System size optimisation	free software, accurate heat and cold network options analysis	"more efficient in management and processing large amounts of data than general simulation tools, more integrated in FME than other GIS tools user friendly for non-profis, intuitive, interactive tool"	already includes different scripts for calculation, automated workflows, major advantage to read and write different data	open source, large user community, support from other users (forum), plug-ins for extending functions	data library, user friendly, less bugs and updates, more robust product (compare with QGIS), plug-ins for extending functions	plattform based, own tailored Apps for clients, management of connectors and platform extensions; 24/7 Online Client portal (helpline)
	Gaps and obstacles	--	--	--	--		non-intuitive interface, limited ability to accurately model thermal mass	Learning curve, detailed whole-building models are complex and slow. Difficult to adjust to rapid changes in the design	Learning curve - experience needed, whole building models are complex and slow, BIM import requires a good quality model or model rebuild	embodied carbon is not included	Temperature cannot be adjusted, Linear investment costs (not able to model increasing costs over time)	Limited flexibility and adaptability due to closed source calculations. Static calculation method is not very precise	Temperature is not adjustable, linear investment costs (not possible to model increasing costs over time)	Uncertainty around ongoing maintenance. Reports should be tri-annual but the last published date was 2016					set up stage takes longer than GIS-software	cost	bugs and regular updates	cost	long implementation process
	Cost for license and subscribtion	--	--	--	--		Free	3000	price on application (dependant on number of licenses)	Free	9000 (5 Licences, 20 Projects)	Free	Free	TIMES is free but VEDA-SYSTEM and GAMS/Solver(s) cost $3000 and $1920, respectively		depending on license type and modules (EnergyPro Design module - standard license 4200 euro/user, one year license 1680 euro/user)	depending on offer (license and user package)	Free	depending on client demand		Free		installation, licence, training necessary
	Handover data to users	--	--	--	--	limited	limited	Dependant on client requirement - may require post processing	Dependant on client requirement - may require post processing	Flexible	limited (xml, html)	limited (report in PDF)		Graphs and data output		limited (xml, report in PDF)	limited (xml, report in PDF)		depending on client demand: low level access, full access to dashboard and high level access to API	very flexible and depends on clients demand	geospatial data or maps as images	geospatial data or maps as images	via apps
	Number of users	--	--	--	--	1 user per local installation	1 user per local installation	1 User per license	individual or unlimited network licences available	1 user per local installation	5 Licences	1 user per local installation	1 user per local installation			1 user per local installation	depending on offer	-	-	depends on subscribtion agreement	-	depends on subscribtion agreement	project dependent

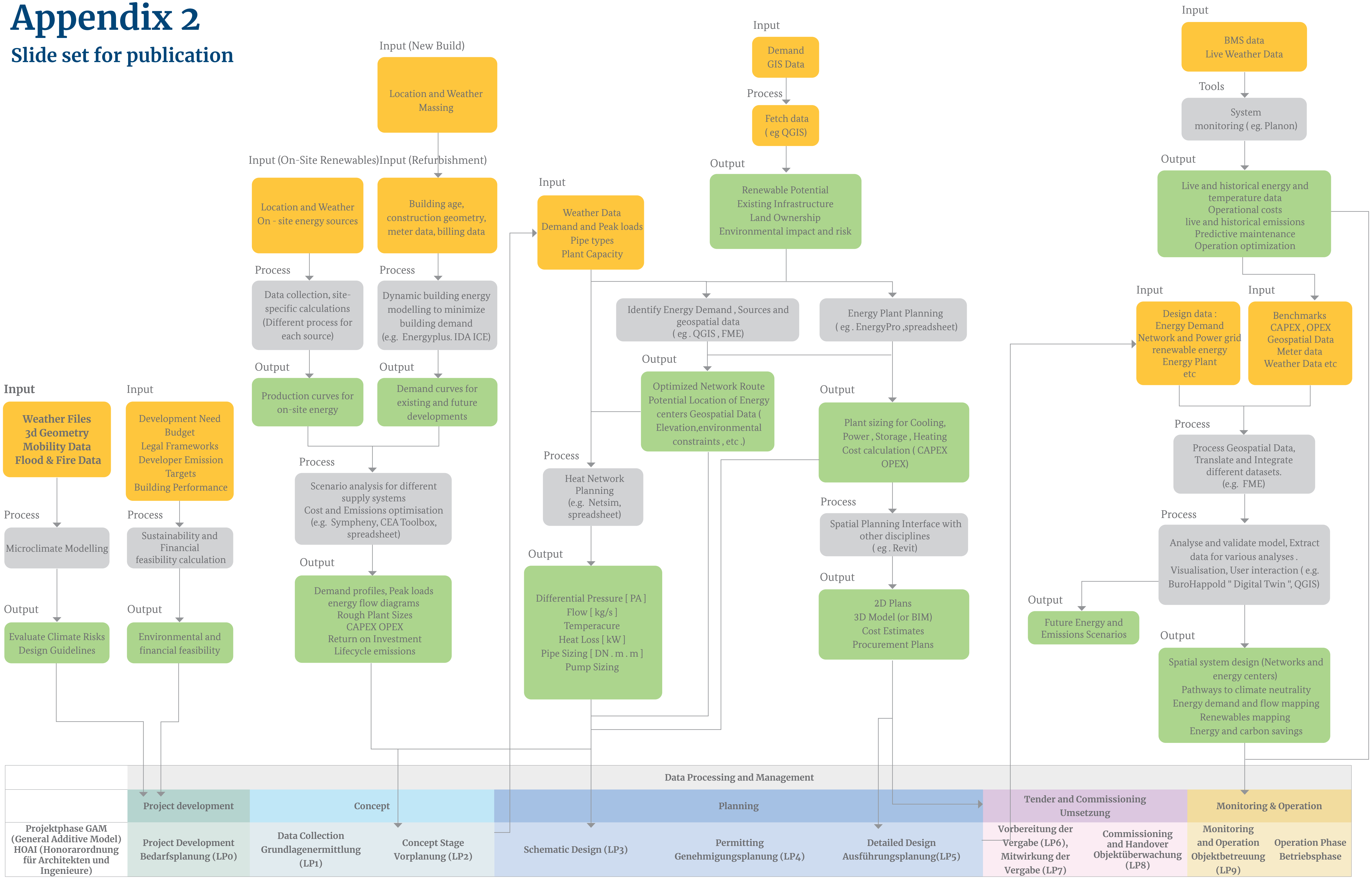
highly relevant to filer criteria

mid-level relevant to filer criteria

less relevant to filer criteria

Appendix 2

Slide set for publication



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