D4.6

PHI District Tool

Report on energy balance district tool,
including the basis of the development for the tool

SINFONIA

"Smart INitiative of cities Fully cOmmitted to iNvest In Advanced large-scaled energy solutions"

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Publishable executive summary

As part of the Sinfonia Work Package 4, the Passive House Institute developed a tool to assess and optimise city districts in terms of energy efficiency. The name of this tool is districtPH.

For reasons of flexibility and transparency, districtPH was realised as an Excel spreadsheet. Building-related energy consumption and the effects of refurbishment measures play a central part. In addition, districtPH considers user-related energy consumptions in buildings. This is supplemented by street lighting and the energy consumption of trams and other electric vehicles. A district heating system and the electricity grid, including short and long-term storages, can be represented. Heat or electricity production in the district, both centrally and in individual buildings, are considered in the total energy balance. Estimation methods for the energy production from renewable sources were integrated.

The development was aiming at two major fields of interest:

- the energy balance of the district, including heat and electricity generators and grids, at a given point in time. Questions such as 'What is required to make the district zero-energy?', 'What would be an appropriate size for a seasonal heat storage?', 'How much energy will be exported from the district in a specific situation?' can be addressed.
- the interaction of current and future retrofits with supply structures. Possible projections include the total primary energy demand or the CO_2 emissions over several decades, depending on different scenarios for e.g. retrofit subsidies or district heating network installations. The probability of a refurbishment to a certain efficiency level can be defined, depending on factors like component age, time, subsidies, or existing efficiency level. The difficulties arising from the probabilistic nature of refurbishment rates were solved by implementing a monte carlo simulation method.

For the current version, due to the inhomogeneous availability of data, it was decided not to develop an import filter for GIS data, e.g. from CityGML. Instead, the buildings in the district are entered by assigning them to one of up to 30 building types, which can either be user-defined or chosen from the Episcope database.

districtPH thus enables the user to investigate, with reference to arbitrary performance indicators, the long-term consequences of planning decisions. This may include creating an increase in the refurbishment rate, changing the quality of refurbishments, realizing or extending a district heating grid, adding renewable energy producers, etc.

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1. INTRODUCTION

As part of the Sinfonia WP4, PHI developed a tool to assess and optimise city districts in terms of energy efficiency. The name of this tool is districtPH. It calculates detailed energy balances for buildings within the neighbourhood and allows interaction with these. Heat or electricity production in the district, both centrally and in individual buildings, is considered in the total energy balance. It is possible to account for public supply structures as well as public consumers.

districtPH is by far not the only software for such a purpose. Its distinctive features include:

- The tool is fully based on Excel, using a few macros, but not relying on any additional software. The software is not in the public domain, but it is open source, all calculations and algorithms are accessible to the user. This makes it particularly flexible. Users can easily add auxiliary calculations or extensions.
- The structure and the algorithms were chosen such as to allow for quick yet realistic calculations. Monthly energy balances for building types and hourly analysis of supply structures in typical situations allow for a hundred simulations of 50 years' length during the user's lunch break.
- Energy use in buildings is a key aspect. The new tool could build on decades of experience from Passive House research. Well-proven algorithms from the [PHPP] could be used in districtPH, simplified for use on the district level and supplemented for example by specifically developed procedures for estimating the effective indoor temperature in existing, poorly insulated buildings.
- A special focus is on the development of the district over time. The probability of a refurbishment to a certain efficiency level can be defined, depending on factors like component age, time, or existing efficiency level.

The development was aiming at two major fields of interest:

- the energy balance of the district, including heat and electricity generators and grids, at a given point in time. Questions such as 'What is required to make the district zero-energy?', 'What would be an appropriate size for a seasonal heat storage?', 'How much energy will be exported from the district in a specific situation?' can be addressed.
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2. A BRIEF LITERATURE REVIEW

In recent years, many research results were published about the field of energy efficiency on district level and the corresponding software solutions. This section summarizes a small selection of publications which were relevant for the development of districtPH.

2.1 OVERVIEW OF PUBLICATIONS

2.1.1 SINFONIA REVIEW BY TECHNOFI

As part of the Sinfonia project, Technofi carried out an extensive literature 'Review of existing decision support tools for district refurbishment' [Laffont 2016]. The authors address the topic on different levels:

- scientific literature related to urban energy modelling
- commercial tools
- current RD&D projects

They evaluated, among others, proceedings of relevant conferences and journals, publications and Ph.D. theses, articles reviewing scientific papers, and references of relevant articles. The literature surveys of several ongoing, EU funded projects for decision support software were taken into consideration: Resilient (CTSB and CEA), Transform (AIT), Ecodistr-ict (TNO), Fasudir (IES), etc.

One major result is the high relevance of input data and their pre-processing. GIS becomes more and more commonplace in municipalities, and the availability of data is likely to improve thanks to the INSPIRE Directive. Nevertheless, there appears to be a wide consensus about the heterogeneity of types and sources of available data, which poses new challenges whenever a tool is to be applied in a new district. Often, different data sources are combined, with possibly conflictual information. Thus, the effort to develop a data model of a city can comprise more than a person-year. This is particularly true because the existing tools are typically case-specific, i.e. adapted to the application for which they have been developed.

About 40 different tools, for building and district level, are listed in a summary and evaluated according to criteria such as status, access, accuracy, or replicability. Most tools apply similar processes for the calculation of energy demands. Several authors report a lack of integrated calculation of the 'link between urban texture and energy consumption'. They suggest that shading and heat island effects be considered.

The authors conclude that there are several tools for every subtask, but that a tool for seamless district energy calculation is still missing.

2.1.2 SINFONIA REVIEW BY UIBK

Also within Sinfonia, [Dermentzis 2016] provided a 'Literature review on energy district tools'. For 11 different tools the authors investigate the focus of the tool (demand, consumption side), its use (forecast or status quo – baseline), open source code or not, organizations developing the tool, calculation method, and architecture. They also describe some case studies.

District tools usually consist of three parts:

- geographical data, e.g. building volume, area, shape, and position. These are mostly 3D geo-data, which are used both for data input and for visualisation of the output.
- physical properties of the building stock, e.g. U-values, air change rate, building type, and user behaviour
- simulation models for the calculation of the energy demand

As for the geographical data, different data formats are mentioned: CityGML with the Energy ADE and the Utility Network ADE; Keyhole Markup Language (KML), as it is used e.g. by Google, industry foundation classes (IFC), and ArcGIS. 3D models have different levels of detail (LoD), classified from LoD 0 to LoD 5. Using the examle of Germany, it is shown that LoD 1 models (building block shape) exist for many locations, LoD 2 (3D model of exterior shape, including roof shape) only on some occasions.

Very different simulation methods are used in the existing district tools, from specific heating demand being based on building type and age only, to detailed dynamic, hourly simulations e.g. with EnergyPlus.

The authors emphasise that historically protected buildings should be considered in a specific way. They also point out that differences between measured energy consumptions and simulation results are often found.

They conclude that the main challenge of a district tool is to find the right balance between accuracy, computational effort, data availability and user friendliness.

2.1.3 INFLUENCE OF MORPHOLOGY

In order to understand the importance of a city's morphology, [Rode 2014] investigated the cities of Paris, Istanbul, Berlin, and London. Starting from the assumption that geometry could be an important factor, they demonstrated that the heating energy use might vary by a factor of 6, depending on the morphology. Compact urban blocks consistently performed best, detached housing worst. The authors found that higher density is correlated to lower heating energy need, with a correlation coefficient of 0.77.

2.1.4 ENERALP / BASELINE INNSBRUCK

The 'baseline' data set for the Sinfonia city Innsbruck was developed by the University of Innsbruck. The methodology, the so-called EneRAlp model, is described in [Pfeifer 2017].

A large number of models for both buildings and cities is described in this study. Semantic city models, i.e. models which have a meaning that extends beyond the pure geometry, e.g. with reference to utilisation, building type or year of construction, have only been described since 2005, but are quickly gaining importance. In many cases they are based on CityGML, a geographical information system data format. Since 2015, CityGML has an energy related extension (Energy ADE). The data that, as of today, are gradually becoming available with the EU INSPIRE directive have a similar structure.

The EneRAlp method follows a bottom-up approach, i.e. the energy consumption of a whole city is calculated from individual energy balances for every single building, from which the total energy demand per sector is derived. The calculation method follows the Austrian standards ÖNORM B8110-6 and ÖNORM H5050.

The study combines many different data sources, such as a digital terrain and surface model, data from energy certificates, population registers and accounting data from the local utilities. Combining these data turned out to be extremely cumbersome. Particular difficulties were encountered due to data protection requirements.

The accuracy that could be achieved was limited by several factors. One problem was the fact that the current condition of a building, e.g. its refurbishment status, was usually unknown. The author decided to use the conditions at the time of erection, which results in a systematic overestimation of the energy consumption. Window sizes, shading factors, room temperatures and thermal mass were estimated because these data were unavailable, too.

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After completion of the data acquisition calibration factors for the heat demand were determined by comparison of the calculation results with actual consumption data from energy bills. For heat these calibration factors turned out to be between 0.4 and 1, with low values, i.e. a strong overestimation of the consumption, particularly for old and for small buildings (data base: 1362 buildings). For buildings where the energy certificate could be used to determine realistic window areas and account for refurbishments, the calibration factors were found to be between 0.6 and 1.5, again with lower values for older buildings (data base: 37 apartment buildings).

A comparison of the calibrated data from the EneRAlp model with the Tabula calculations ([Tabula 2018]) revealed a significant overestimation of the consumptions by the Tabula method. The authors attribute this difference to room temperatures, refurbishment measures and vacancies unaccounted for in the Tabula model.

2.1.5 DEMAND SIDE MANAGEMENT / DEMAND RESPONSE

In future energy systems, which will mainly be built on fluctuating renewables, it will be of interest to shift loads, particularly electrical loads, to times when renewable energy is readily available, instead of using expensive storages. [Neubarth 2017] provided a literature overview and some useful expert assessment in this field.

First, it must be noted that results for load shift potentials cannot simply be transferred from one country to another. The load shift potential depends on a large number of factors, e.g. the climate, the type of household appliances, the fraction of different sectors in the electricity consumption of commerce and industry. It is preferable to relate load shift potentials to applications, e.g. washing machines and dishwashers in households, ventilation and cooling in supermarkets.

The load shift potential is strongly reduced with increasing duration. Shifting loads for 15 minutes or even a few hours is possible in most applications, but shifting loads for more than 24 hours is rarely possible ([Wedler 2013]).

In addition, the order of magnitude of these potentials is rather limited. Estimates are ([Neubarth 2017]):

- Households 6% (including DHW and space heating, of which consists the major fraction)
- Commerce, trade, services: 3%
- Industry: 1%

Technically, the use of washing machines, clothes dryers, and dishwashers in a household could be shifted over longer periods, provided that it is possible to influence the user behaviour accordingly. At current energy prices, with a typical consumption of 1 kWh per application, this is not expected. Since the majority of the energy consumption of these applications is caused by hot water production, technical solutions like integrated thermal storages are theoretically possible. However, it is expected that this would take up a lot of space and cause considerable additional cost.

Peak load reductions in households of about 5% are reported, including with manual implementation ([Elbe 2014]).

The energy demand for electrical DHW production can be shifted significantly. For larger electrical boilers the electricity use can be shifted by approximately 24 hours. It is expected that 50% of the average electricity consumption for this application can be shifted.

Similarly, it is possible to shift space heating consumptions within the day. This has been common practice with off-peak storage heating for a long time, but concrete core activation and/or highly insulated buildings are seen as an option. When heat pumps are used, load shifts may result in an increase of electricity consumption by 5 to 10%.

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Significant electrical peak load reductions of up to 40% were measured in the USA, with typical values of 4 to 17%. This is mainly attributed to air conditioners and appears to occur on few days per year only, when there is a strongly increased 'critical peak price' ([Elbe 2014]). OhmConnect, for example, offers prices of 1 to 3 $/kWh to California customers for every kilowatt-hour that is not consumed, during one or two peak hours per week. Savings of up to 800 $ per year are reported, which means that approximately 10 kW of power are turned off during the respective hours. In Europe, such savings can only be expected under exceptional conditions.

The demand response potential of electrical passenger cars cannot be assessed from experience as of yet. If sufficiently large batteries are used, the potential will be correspondingly high, because users will not need to charge their vehicles every day. Apart from public charging stations, where instantaneous charging is typical, electric vehicles will often remain stationary for at least 8 hours at home or at work, but need only 1 or 2 hours for charging ([Neubarth 2017], [Elbe 2014]).

2.1.6 LOAD PROFILES

For the calculation of peak loads and of the distribution of loads to different heat or electricity generators it is necessary to know which load occurs at a specific day of the week and time of the day. Electricity utilities typically use so-called standard load profiles for similar purposes. These profiles show the fraction of the total electricity load that occurs in a particular hour.

[Weissmann 2016] points out that there are different types of load profiles for different applications. For residential buildings he mentions

- VDI 4655 with exemplary profiles of individual buildings are suitable for calculating which fraction of a building's electricity consumption can be covered by electricity generated on site.
- BDEW/VDEW provide standard load profiles that represent the average consumption of a large group of similarly used buildings.

Indeed, these types are fundamentally different. For district energy balances the second type is required. According to [Pflugradt 2016] the standard load profiles can be used if an average of several thousand households is considered. However, he shows diagrams that indicate an applicability even for only 100 households.

Pflugradt also mentions that the load profiles have changed during the last decades. Examples include IT electricity consumption in households and shop opening hours.

Daily load profiles for district heat consumption could not be found. The ambient temperature appears to have a higher influence on the load in a district heating network than the time of day.

2.1.7 OVERESTIMATION OF HEATING ENERGY CONSUMPTION

During the last years an increasing number of publications from different countries became available on the difference of calculated heating energy demand and actual heating energy consumption. Most of these investigations show a significant overestimation of heating consumption for old and small buildings, and a smaller underestimation for buildings with a very low heating demand. Some relevant publications and meta-studies can be found in report listed in Appendix 2. This list shall not be repeated here.

2.2 CONCLUSIONS

The most relevant results from the literature survey can be summarized as follows:

- A large number of tools for district energy balances is already available. Usually, these tools are case-specific and have only been applied for individual cases. The application usually takes several months.

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- Building types have a large influence for the heating energy demand. It is crucial to represent different building types and states. Similarly, the shading situation needs to be accounted for.
- Due to the heterogeneity of types and sources of available data it does not appear useful to develop specific import filters, GIS-related import tools, etc. Instead, manual selection and assignment of the buildings in the district was preferred.
- Standard calculation procedures tend to overestimate the major influencing factor, the energy consumption for space heating. Special attention is dedicated to this topic in the development of districtPH.
- Detailed demand response models did not appear appropriate for districtPH due to the limited potential and high possible inaccuracies. However, an option to declare district heating and electricity demands as flexible within one day was implemented. Electric vehicles are also considered to have an optional fraction with a 24 h load shift capability.
- Using standard load profiles from the literature for the electricity consumption of many similar consumers appears to be the best available option for the application within districtPH. Load profiles for heating, DHW and cooling have to be estimated.
- Special attention should be paid to listed buildings, where not all components can be refurbished.

3. BASIC STRUCTURE OF DISTRICTPH

For reasons of flexibility and transparency, districtPH was realised as an Excel spreadsheet. Building-related energy consumption and the effects of refurbishment measures play a central part. In addition, districtPH considers user-related energy consumptions in buildings. This is supplemented by street lighting and the energy consumption of trams and other electric vehicles. A district heating system and the electricity grid, including short and long-term storages, can be represented. Estimation methods for the energy production from renewable sources were integrated.

For some purposes algorithms from the [PHPP] could conveniently be integrated, many other methods were developed from scratch. We assumed that the data acquisition would not be as accurate as when planning a new building. Design drawings will not be available, neither will exact component qualities, numbers of inhabitants, etc. Once accepted, this fact allows for entering the buildings in the district by assigning them to certain pre-defined building types from a typology.

For the current version, , due to the inhomogeneous availability of data, it was decided not to develop an import filter for GIS data, e.g. from CityGML.

One of the major goals in the development of districtPH was the prediction of how the district's energy demand evolves over time. Since future developments will always depend on many currently unknown parameters, the calculation results will have an unavoidable inaccuracy, which in turn justifies time-saving simplifications of the calculation methods themselves. The resulting inaccuracies are only of minor importance for practical purposes: What is relevant for decision-making are the advantages of certain strategies in comparison to others, not so much exact predictions of the energy consumption in absolute figures.

The first step in setting up an energy balance is to enter the buildings in the district. Each building is assigned to one of up to 30 building types, which can be either user-defined or chosen from the Episcope database ([Tabula 2018]). The buildings with their type, their positions and square meters of floor area can be entered. The building types already contain efficiency levels for all building components and the mechanical systems.

Excel can now calculate the energy balance of each building type with regard to heating, cooling, hot water, and electricity, and report the sum totals of e.g. delivered energy, CO_2 emissions, or source energy. The relevant results are saved, and the district moves on to the next year. Now, with a user-defined probability, a retrofit of the building components to a different efficiency level takes place, and the calculation process starts again.

In order to deal with the exponentially growing number of buildings from year to year, a Monte Carlo method was selected: The number of building types remains constant in every time steps, with each building type having only one renovation status, determined by retrofit probabilities. The whole simulation is repeated several times, with different random numbers, until the average of all individual results for the required quantity has been determined with sufficient accuracy.

This core calculation process is supplemented by several additional tools:

- an import filter from the PHPP, for defining a building type from existing PHPP input data
- a variant management, allowing for a comparison of e.g. different supply structures
- an economics calculator, suitable to determine economically optimal renovation measures
- a climate data worksheet, where local climate data can be entered
- a set of worksheets for an hourly analysis of electricity and district heating networks

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4. BUILDING MODEL

4.1 PARAMETERS OF THE BUILDING STRUCTURE

Several different considerations influenced the decision on the structure of building model data.

- It should be possible to set up a model for a whole district in a short time. Input of the buildings and building types should be simple and fast.
- The available data will usually not be very detailed. Construction drawings will not be available.
- To allow for a comparison of refurbishment scenarios, many buildings need to be calculated over many years in many variants, multiple times. The calculation model has to be extremely fast.
- Building have to be aggregated to building types, with a certain inevitable loss of accuracy.

It becomes clear that only simple models could be used in districtPH. Even the input for a PHPP calculation would be inappropriate, let alone the additional detail for a dynamic simulation.

The building types' description is therefore limited to the following information:

- building age class
- treated floor area
- number of storeys
- number of dwelling units
- area and U-value of 2 roof types, 3 wall types, 2 floor types, 1 entrance door type
- area of 5 windows, horizontal and facing the four cardinal points
- U-value and g-value of windows
- thermal bridge supplement
- airtightness, characterized by the blower door result n50
- efficiency of heat recovery, if any
- temperature setpoints for heating and cooling (only for non-residential buildings)
- number of persons (only for non-residential buildings)
- internal heat gains (only for non-residential buildings)

This level of detail is sufficient to calculate the useful energy demand for heating and cooling, both for residential and non-residential buildings.

4.2 HEATING

The model for calculating the heating demand is based on a monthly energy balance according to [EN ISO 13790]: Month by month, heat losses at the temperature setpoint are calculated. Internal and solar heat gains are multiplied by a utilisation factor and then subtracted from the heat losses. The remainder needs to be supplied by the heating system.

This methodology has proven its validity in a large number of realized Passive Houses. For buildings with a lower energy standard, the temperature setpoint needs to be modified (cf. section 4.4). The heating worksheet from the PHPP was used as a basis for the calculation.

4.3 COOLING

If an active cooling system is installed in the building, the cooling demand is calculated following a similar procedure as for the heating demand. Again, the temperature setpoint depends on the insulation level.

Any possible dehumidification demand is calculated alongside the cooling demand.

4.4 REALISTIC CALCULATION OF HEATING DEMAND

For residential buildings, following the methodology described in [Schnieders 2018], an effective room temperature setpoint is determined depending on the insulation level. This temperature accounts for partial heating both of different rooms and at different times, as well as for other influences that were found in the comparison of measurements with energy balance calculations.

Non-residential buildings, e.g. indoor swimming pools or storage facilities, can have different levels of temperature. For these buildings the heating and cooling temperature setpoints need to be added as part of the building type description in the typology.

4.5 DOMESTIC HOT WATER (DHW)

The useful energy for DHW production is assumed to be 25 l per person per day at 60 °C for residential buildings. In non-residential buildings, this value is reduced to 5 l.

4.6 MECHANICAL SYSTEMS

Mechanical systems are implemented with a similar level of detail and accuracy as the building envelope. The following data are required for every building:

- energy carriers and total system efficiency, separately for heating, DHW, and cooling
- efficiency level of use of other electricity, e.g. for domestic appliances in residential buildings
- for non-residential buildings, a reference electricity demand is required as an additional input
- utilisation profile for heating, DHW, and electricity

Different systems are directly represented by different efficiencies, with default values being provided for the most important system types. Electrical heating, for example, can mean that an electrical resistance heater is installed (efficiency 100%), but it can also refer to an air-source heat pump (efficiency 200 - 300%) or a ground-source heat pump (efficiency 300 - 500%). Drain water heat recovery can be represented by an improved efficiency of the DHW system, etc.

4.7 AUXILIARY ELECTRICITY

Auxiliary electricity is mainly required for circulation pumps, but also e.g. for fans, control systems, defrosting or crankcase heaters. The fraction of auxiliary electricity, as part of the total useful energy produced, can be close to negligible, like in modern high-quality hydronic heating systems. However, it can also make up a fraction of 5% in older heating systems, let alone systems like absorption chillers. Therefore, a fraction of auxiliary electricity is assigned to every heating, cooling, or DHW system.

Auxiliary electricity consumptions of solar domestic hot water systems are also considered, using a fraction of 5% of the useful heat produced.

For ventilation systems with heat recovery it is assumed that the electricity demand is correlated with the thermal efficiency, with high-efficiency ventilation units having more efficient fans as well. A correlation following

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$$P_{el} = 1.25\,\frac{Wh}{m^3}\left(1 - \eta_{heat\ recovery}\right)\dot{V}$$

is assumed here.

4.8 EFFICIENCY LEVELS

In order to allow for a comparison of refurbishment strategies and the resulting energy consumption it is necessary to find an abstract description of these strategies (cf. section 5). For this purpose it turned out to be appropriate to group the efficiency levels of building components into classes. We chose a pattern with 9 groups which are numbered from 1 (usually the worst standard) to 9 (usually the best). The following table shows an example.

EFFICIENCY CLASSES FOR WALL ASSEMBLIES									
CLASS NUMBER	1	2	3	4	5	6	7	8	9
U-VALUE (W/(m²K)	4	2	1.5	1	0.6	0.3	0.2	0.15	0.1

This type of group assignment applies to the components of the building envelope, such as walls, roofs, windows, as well as to the mechanical systems.

4.9 RENEWABLE ENERGY PRODUCTION

Renewable energy can be produced on the building in different variations. The following options are available in districtPH:

- no renewables
- solar thermal for DHW only
- PV only
- solar thermal for DHW + PV
- solar thermal for DHW and heating
- solar thermal for DHW, with excess heat provided for district heating
- solar thermal for DHW and heating, with excess heat provided for district heating

The energy yield of these systems is calculated building by building, but, for reasons of simple use, without further user input. The following assumptions are made: Solar thermal collectors and PV modules have a default inclination towards the equator, and only a default fraction of the gross roof area is available for renewables. There are no additional heat losses from the solar DHW storage because, although the solar storage may be bigger than the conventional storage it replaces, it will usually have a better insulation. Solar hot water is produced with a standard flat plate collector, and modules made from monocrystalline silicon provide photovoltaic electricity.

If only DHW is produced, no more than 1.5 m² of collector area per person is assumed. If heating support is chosen, the fraction of the roof which is available for renewables is fully dedicated to this purpose. Whatever part of the roof's available fraction is not required for solar thermal can be used for PV.

Concerning the roof area that is available for solar energy use, default factors were determined according to the following considerations: For Germany, deviations from the optimum orientation by up to ±75° or, alternatively, from the optimum inclination by up to ±35° reduce the solar radiation sums by less than 10%. A few experiments using the f-chart method for calculating the yield of solar thermal systems resulted in the following conclusions:

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- A similar relation holds for the solar thermal energy production, depending on the orientation, as it does for the solar radiation sums.
- For flat roofs, it may be assumed that the whole roof is available for solar energy, except for roof windows, anchorage points, ventilation units, skylights, the areas of roof parapets, etc.
- For a saddle roof with the two roof areas pointing north and south, only one of the roof areas will be used. Because of the more favourable orientation and the larger total roof area, the solar gains are still 60 to 80% of the gains on the horizontal roof.
- If the two roof areas face east and west, both roof areas are likely to be used. In this case, the yield would even be higher than on a flat roof, by 10 to 20%, albeit at higher investment cost.

It may be concluded that the amount of solar energy that can be harvested on a roof mainly depends on the horizontally projected area. With acceptable accuracy, the actual shape of the roofs is not required for the calculations in districtPH.

[UBA 2010], in a careful estimate, assumes that 25% of the total roof area receive sufficient solar radiation for PV installations to be feasible, with 70% of that area actually being available (due to chimneys, installations, etc.). In [Gertec 2008], 40% of the horizontally projected roof area are considered suitable for solar energy use, with solar radiation sums above 1000 kWh/(m²a).

As a default value in districtPH, 50% of the building's footprint area are assumed to be available for a horizontally oriented solar collector or PV installation. 30% are deducted from this area for skylights, chimneys, etc. The default shading factor for these installations is 0.9.

5. EVOLUTION OVER TIME

One of the major goals in the development of districtPH was to provide a means for investigating the evolution of a district over time. The renovation rate of different building components depends on political boundary conditions, the economic situation, legal requirements, the age and status of the building stock, etc. In any case only a (usually small) fraction of the buildings of a certain building type will be refurbished in a particular year. A suitable methodology to deal with this situation needed to be developed.

5.1 NOT SUITABLE: CALCULATING EVERY BUILDING BY ITSELF

In principle, the calculation could be carried out separately for every building in the district, using its specific geometry, mechanical services, building components, and use. Usually, such an approach would be far too time-consuming; gathering the required information and setting up a suitable energy balance may be expected to take more than one day's work per building.

Even if only building types are addressed, another problem occurs with such an approach: Future refurbishment actions can only be known with a certain probability, which means that different runs need to be carried out as described in section 5.3. In that case, as will be explained below, it is not necessary to explicitly consider each building.

5.2 NOT SUITABLE: PRECALCULATING ALL COMBINATIONS

It is convenient, both in tems of data acquisition and calculation times, to assign every building to a building type of a typology. The probability of component refurbishments to a certain efficiency level is then considered for each building type.

A possible algorithm that reduces the required calculation time to a minimum can be described as follows: Every component of the building is assigned to one of a limited number of efficiency levels, as described in section 4.8. Each individual building's state is then described by a set of efficiency levels for all of its components. The finite number of combinations allows for a pre-calculation of the

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energy consumption for every combination, which could be done without further user interaction. Afterwards, depending on the probability of refurbishment, only the (not necessarily whole) number of buildings of a specific component combination changes.

One big advantage of this approach is that refurbishment probabilities can be considered, but the calculation result is determinate nevertheless.

Unfortunately, it turned out that the number of possible combinations becomes very big: If 10 building types with 10 possible states for wall, roof, floor, window, and ventilation, and 10 variants of the mechanical services for heating and DHW are considered, this already results in $10^{(1+5+2)} = 10^6$ combinations. Any additional building parameter would again multiply the number of variants by 10. The requirements for calculation capacity and storage would thus quickly become very inadequate.

5.3 MONTE CARLO METHOD

Based on the above considerations a so-called Monte Carlo method was chosen for the investigation of scenarios: Only one instance of each building type is considered. The change of its status from year to year, based on the refurbishment probabilities, is observed and the results of interest are recorded. If this procedure is repeated sufficiently often, the average of all results represents the expected value of the result sufficiently well. The standard deviation of this average can easily be calculated from the results of each Monte Carlo run. It is therefore possible to adjust the number of runs to the desired accuracy of the result, or to the required selectivity in cases where different scenarios are to be compared.

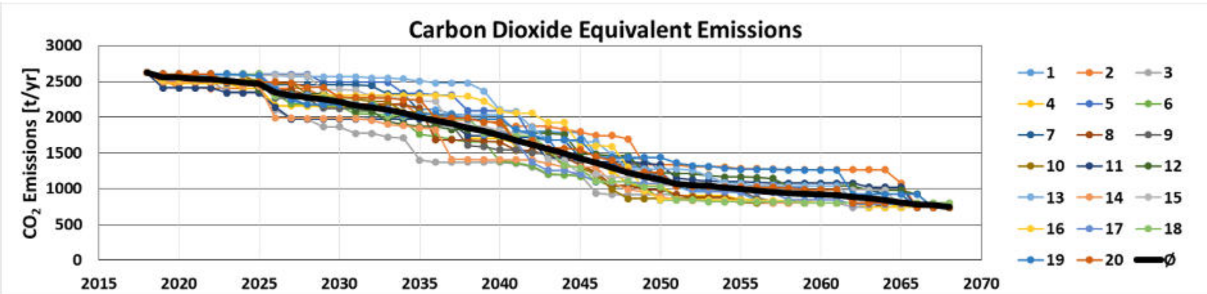

FIGURE 1. 20 DIFFERENT MONTE CARLO RUNS FOR THE CO_2 EMISSIONS IN A REFURBISHMENT SCENARIO. THE THICK BLACK LINE REPRESENTS THE AVERAGE OF 100 RUNS.

5.4 PROBABILITIES FOR REFURBISHMENT

From the above it is clear that each component (roof, wall, windows, heating system, etc.) has a certain probability of being refurbished to a certain efficiency level at the end of the year that is currently considered in the simulation. This probability depends on the age and, often to a lesser degree, on the efficiency level of the component. For simplicity, districtPH divides this probability into two parts:

- Will there be any renovation of the component at all?
- If so, which will be the new efficiency level?

For the first question, it appeared appropriate to allow for a probability distribution, too. The Weibull distribution, which is zero for negative arguments, appeared appropriate. Its two parameters can roughly be correlated with the average lifetime of the component and with the spread around this average. These data can be entered by the user.

The implementation starts from the cumulative distribution function. It gives the probability that a component has been renovated at least once after *n* years. Figure 2 shows a typical example.

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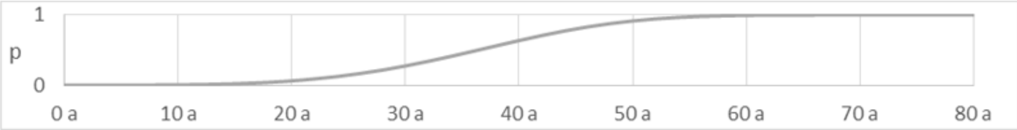


FIGURE 2. CUMULATIVE WEIBULL DISTRIBUTION FUNCTION FOR AN AVERAGE LIFETIME OF 50 YEARS AND A SPREAD OF 12.5 YEARS. THE CURVE SHOWS THE PROBABILITY P THAT AT LEAST ONE RENOVATION HAS TAKEN PLACE AFTER THE SPECIFIED TIME.

Since there can be only one renovation per year in the model it is necessary to discretise the distribution function. Let $p_k(n)$ be the value of the cumulative distribution function at an age n, and $p(n)$ the probability of a renovation at the age n. Then $p_k(n)$ is a sum of two probabilities: that the component has been renovated before the year n, and that it is renovated in the year n but has not been renovated before. Thus

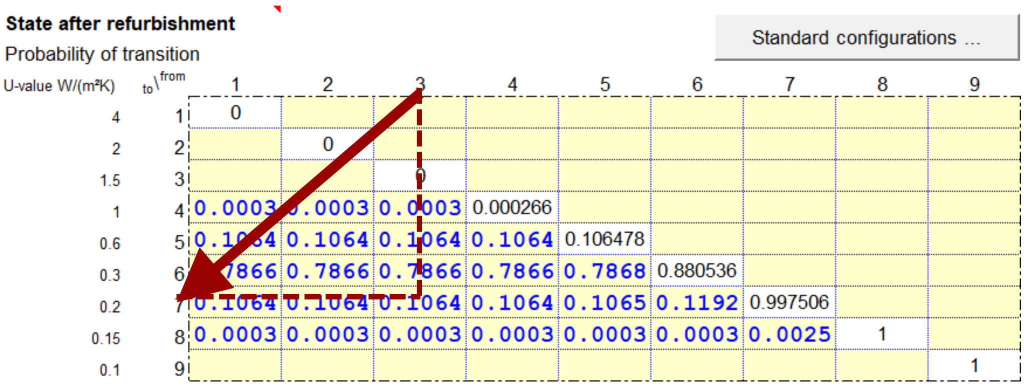
$$p_k(n) = p_k(n\text{-}1) + (1\text{-}p_k(n\text{-}1))p(n)$$

By rearranging this equation, $p(n)$ can be found as a function of the cumulative distribution.

Mind that $p(n)$ is not the probability density function. The latter, when integrated over a certain period of time, relates to the probability that a newly installed component will be renovated during this period. The calculation, on the other hand, requires the probability that a certain component is renovated in the current year *if no renovation took place before*. This latter probability increases from year to year, whereas the probability density function always declines after a certain point in time.

The second question, concerning the new efficiency level, is answered by an additional probability matrix. Figure 3 shows an example: If the wall has an efficiency level of 3, equivalent to a U-value of 1.5 W/(m²K), the probability that its efficiency level will change to 7 (U-value 0.2 W/(m²K)) is 10.64% – if a renovation takes place at all.

It may also happen that a renovation does take place because the lifetime of the component is reached, but that no improvement to the efficiency level takes place. This is reflected by a non-zero value in the main diagonal of the probability matrix. In such a case, only the age of the component is reset to the current year.



State after refurbishment

Probability of transition

Standard configurations ...

U-value W/(m²K)	to\from	1	2	3	4	5	6	7	8	9
4	1	0								
2	2		0							
1.5	3			0						
1	4	0.0003	0.0003	0.0003	0.000266					
0.6	5	0.1064	0.1064	0.1064	0.1064	0.106478				
0.3	6	0.7866	0.7866	0.7866	0.7866	0.7868	0.880536			
0.2	7	0.1064	0.1064	0.1064	0.1064	0.1065	0.1192	0.997506		
0.15	8	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0025	1	
0.1	9									1

FIGURE 3. THE PROBABILITY OF A TRANSITION FROM ONE LEVEL TO ANOTHER CAN BE FOUND FROM THE PROBABILITY MATRIX

5.5 ECONOMICS

In districtPH, the probability of a transition can also be determined purely from economic considerations. When the user chooses a corresponding option, any refurbishment takes place according to the economic optimum. In many cases, this means that the component will only be renovated at the end of its lifetime.

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A dynamic lifecycle analysis which determines the lifecycle cost for every possible transition (including no renovation as well as renovation to the existing efficiency level) was integrated. From this calculation it can be seen which refurbishment at which point in time is economically optimal.

The analysis follows [Ebel 2013] and requires the following data:

p	real interest rate or adequate target rate
s	annual increase of energy prices; the cost of refurbishment is assumed to increase with the real interest rate only
n	period under consideration
N	economic lifetime or utilisation period
B	present value
K	net present value, i.e. the sum of all present values
$D(p,\mathrm{m})$	discount factor at an interest rate of p after m years; this is the ratio of the present value of a payment in the year m to its (real) value
$B(p,n)$	present value factor for constant payments over n years at a real interest rate of p; this is the present value of annual payments with a real value of 1 over n years
$B(p,n,s)$	present value factor for annually increasing payments
P_i	annually recurring payments, in particular energy cost
I	non-recurring investment, in particular efficiency measures
I_0	investment cost which is always incurred if a building component is renovated
ΔI	investment cost due to improved energy efficiency
$r(p,n,N)$	residual value factor at an interest rate of p, calculation period n and lifetime N; this value can be negative if one or more reinvestments become necessary during the calculation period

From [Ebel 2013], the following holds:

$$D(p,m) = (1+p)^{-m}$$

$$B(p,n) = (1-(1+p)^{-n})/p$$

$$B(p,n,s) = B((p-s)/(1+s),n) = (1+s)*(1-(1+(p-s)/(1+s))^{-n})/(p-s)$$

$$= (1+s)*(1-((1+s)/(1+p))^{n})/(p-s)$$

$$r(p,n,N) = 1-B(p,n)/B(p,N)$$

As a matter of principle, real cost, i.e. cost adjusted for inflation, is considered. We investigate the case of a building element of a utilisation period N, where N can also be longer or shorter than the calculation period of n years length.

A component which is replaced at the beginning of the calculation period and which is used until the end of the calculation period has a net present value of

$$K_0 = (I_0 + \Delta I) + P_{i,after}*B(p,n,s)$$

If $n \neq N$, a residual value correction is required according to

$$K_0 = (I_0 + \Delta I)*(1-r(p,n,N))+ P_{i,after}*B(p,n,s)$$

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If, on the contrary, the component is replaced or refurbished after *m* years, the following net present value results:

$K_m = (I_0 + \Delta I)*(1-r(p,n-m,N))*D(p,m) + P_{i,before}*B(p,m,s) + P_{i,after}*B(p,n-m,s)*D(p,m)/D(s,m)$

where $P_{i,before}$ and $P_{i,after}$ refer to the energy cost before and after the time of the renovation measure.

In a first step the economically optimal efficiency level of a component is determined, i.e. that efficiency level which, under the given boundary conditions, results in the lowest total net present value of investment and energy cost. This level is independent of the component's current efficiency level and of the remaining lifetime of the existing component. In other words, whenever a refurbishment takes place, it is the same efficiency level which results in cost optimality. This is easy to see: the optimum is reached if additional insulation is not profitable any more. This point is independent of the starting point. If, however, there is an additional increase in energy cost ($s \neq 0$), the position of the optimum may depend on the time of refurbishment. The length of the calculation period can also influence the position of the optimum – in spite of the fact that residual values are accounted for – if there is a real increase in energy cost.

When searching for the economic optimum it may therefore be assumed that if a refurbishment takes place, it will be to the above optimum efficiency level. This means that only two variants – no change or change to the optimum efficiency level – need to be considered further, which simplifies the following calculation significantly.

The second step of the economic calculation is to decide whether a component should be renovated in the current or in a later time step. If the component is renovated immediately, the residual value of the existing component is lost. However, the corresponding costs have already incurred earlier, a fact that cannot be changed. These sunk costs are therefore not explicitly considered in the calculation. Instead, in comparing variants, it is considered that a component which is renovated later has a higher residual value at the end of the calculation period. In addition, the present value of a later investment is lower.

In practically relevant cases the best option, economically seen, is not to refurbish the component before the end of its lifetime (Figure 4)

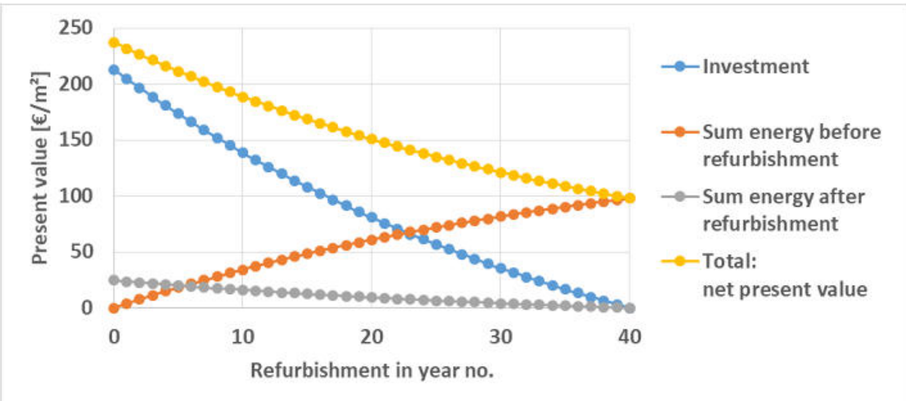

FIGURE 4. BREAKDOWN OF INVESTMENT AND ENERGY COST DEPENDING ON THE YEAR OF REFURBISHMENT (p = 2.5%, s = 0%, n = N = 40 yrs., I_0 = 190 €/m², BEST REFURBISHMENT AT END OF LIFETIME)

An immediate renovation is advantageous if $K_0 \leq K_i$ for all i from 1 to *m*. This may happen if I_0, the cost of renovation that is independent of the efficiency level, is small compared to the possible energy savings (Figure 5).

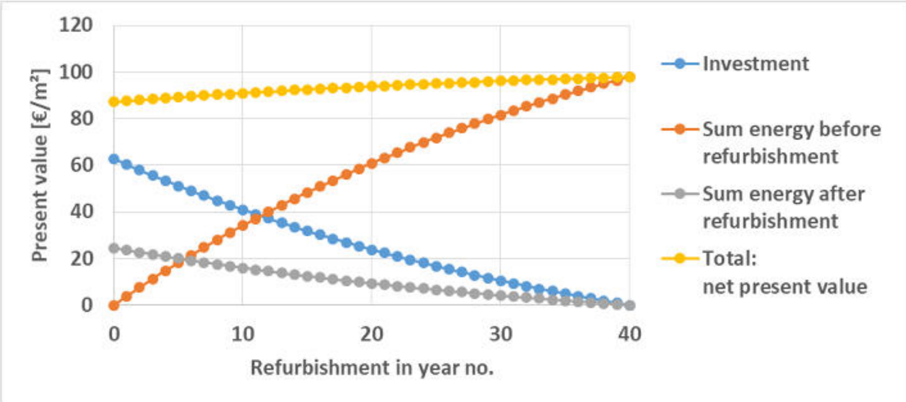

FIGURE 5. BREAKDOWN OF INVESTMENT AND ENERGY COST DEPENDING ON THE YEAR OF REFURBISHMENT (p = 2.5%, s = 0%, n = N = 40 yrs., <u>I_0 = 40 €/m²</u>, BEST REFURBISHMENT IMMEDIATELY)

If the increase of energy prices *s* is greater than zero there are cases where a certain type of refurbishment is best realized neither in the current year nor at the end of the utilisation period, but at some time in between (Figure 6).

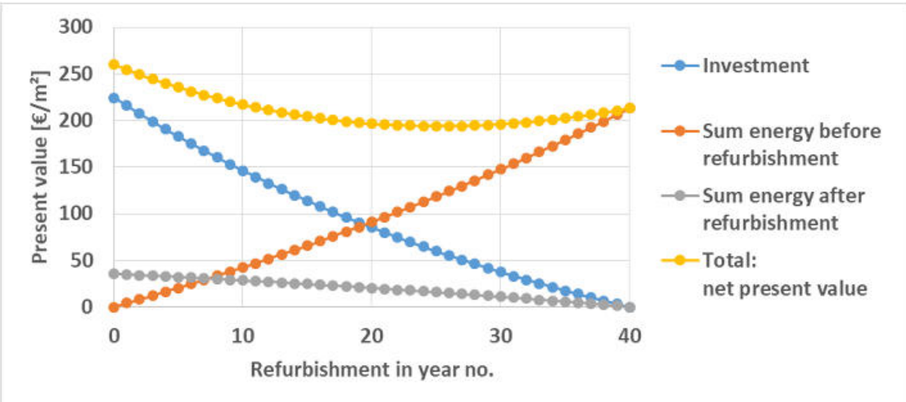

FIGURE 6. BREAKDOWN OF INVESTMENT AND ENERGY COST DEPENDING ON THE YEAR OF REFURBISHMENT (p = 2.5%, <u>s = 4%</u>, n = N = 40 yrs., I_0 = 190 €/m², BEST REFURBISHMENT AFTER 25 YEARS)

It can be shown that in such a case renovation in the next year is already advantageous over renovation in the current year, i.e. K_0 is always greater than K_1. Consequently, an immediate renovation is not the best solution, which is all the algorithm needs to know in the current year.

Thus, it is sufficient to calculate the net present value for three cases:

- renovation in the current year
- renovation in the following year
- renovation at the end of the utilisation period of the existing component

The component will be renovated in the current time step only if this is the best of the three options. This includes the case when the utilisation period ends in the current year anyway.

In theory, there may be cases where the economic optimum has a lower efficiency than the existing component, although this will not occur very frequently. A reduction of the efficiency level can only occur at the end of the component's lifetime because otherwise additional cost would result for both, investment and energy. It depends on the individual case if the new component will really have a lower efficiency level than the existing component. In some cases existing insulation may remain in the construction even if the exterior plaster or a roof membrane needs to be replaced. Exchanging a window, on the contrary, will always mean that the properties of the existing component are lost.

Adding an additional input option to distinguish between these situations would have increased the complexity of the data input; instead, it is generally possible that the new efficiency level is lower than the old one.

6. ENERGY SUPPLY

This section deals with the production of heat and electricity in their respective networks and, in particular, with methodologies of assessing different types of heat and electricity generation.

6.1 ELECTRICITY SUPPLY

Electricity can either be produced within the district or provided from the outside. Several power plants, with different capacities and availabilities, may be involved.

There are different methods for assessing the electricity consumption and production and for comparing one supply scenario with another one. In districtPH, the following are available:

- absolute values of electricity consumption and production
- absolute values of the consumption of different energy carriers
- non-renewable primary energy and CO_2 emissions. This is a widespread method with certain weaknesses.
- PER (Primary Energy Renewable), an assessment of energy consumption and production under the assumption of a future, fully renewable energy supply

In principle, the Excel basis of districtPH allows for arbitrary additional assessment methodologies to be added by the user.

6.1.1 DISTRIBUTION LOSSES

Electric transmission losses can be on the order of several percent of the consumption, particularly when electricity is transported over longer distances. Within a district, however, over distances of a few kilometers, transmission losses can be assumed to be much smaller than the unavoidable inaccuracies in the input data. This may be different for electricity that is imported into the district. For this type of electricity, however, primary energy factors etc. already include the corresponding transmission losses. Therefore, electric transmission losses are not explicitly accounted for in districtPH.

Similarly, losses of transformers could have been of interest, but it was found that the losses of large power transformers are small enough to be neglected.

6.1.2 NON-RENEWABLE POWER PLANTS

For conventional power plants based on fossil or renewable energy carriers a fixed efficiency can be entered.

6.1.3 PHOTOVOLTAIC SYSTEMS (PV)

The yield of PV systems is calculated following algorithms that are also used in the [PHPP].

6.1.4 WIND ENERGY

The energy that is produced by a wind turbine can be calculated, with good accuracy, as

$$P = \frac{\rho_{air}}{2} \cdot c_P \cdot A \cdot v_{hub}^3$$

ρ_{air}	= density of air, ca. 1,25 kg/m³
c_P	= coefficient of performance, typically 45%
A	= cross sectional area of the wind turbine
v_{hub}	= wind speed at the hub height of the wind turbine

The wind speed at hub height can be estimated from wind speeds measured at other heights according to the wind shear formula:

$$v_{hub} = v_r \cdot \frac{\ln(\frac{z}{z_0})}{\ln(\frac{z_r}{z_0})}$$

where

v_r	= wind speed at reference height
z_r	= reference height, often 10 m
z_0	= roughness length, typically 0,1 m
z	= hub height

An economical operation of wind turbines is usually not possible at average wind speeds that are below 4 m/s.

The cubic relation between wind speed and power production results in strong variations of the electrical power. In order to take these variations into account, a typical weekly wind speed profile was extracted from the 2010 version of the German test reference years for Hof, Germany. The user can replace it by other wind profiles, including whole-year measurements.

The average wind speed depends strongly on the location. A simple evaluation of German test reference years, even if exceptions like mountain tops are neglected, resulted in average wind speeds at 10 m height between 2 and 5 m/s, depending on the location and the season.

Primary energy and CO_2 factors for wind turbines can be calculated from the energy required for construction, operation, and demolition of the turbine, weighted with the current energy mix, and from the electricity produced. Results from such calculations for different locations can be found e.g. in [GEMIS 2004]. Assuming a fixed lifetime of the installation, the factors depend on the full load hours according to

PE factor = energy required for construction / (nominal capacity * full load hours)

The energy required for the construction etc. of a specific wind turbine is usually not known. It appeared sufficient to estimate the typical ratio of the energy required for (or the equivalent CO_2

emissions caused by) construction to the nominal capacity. This was done based on data from [Rausch 2012] and [Statista 2018]. This allows for the calculation of PE and CO_2 factors for arbitrary configurations.

6.1.5 COMBINED HEAT AND POWER (CHP)

CHP plants produce both heat and electricity, usually at a fixed ratio. The heat and electricity demands are usually not matching the generation, which means that there can be different operation strategies for the CHP. One option is to run the system heat-driven, i.e. the unit operates whenever there is heat demand, and it feeds the co-generated electricity into the grid. The other extreme is to provide electricity whenever it is needed, which means that part of the generated heat is wasted, leading to a relatively poor overall efficiency. More complex operation strategies are possible, but the usual procedure is a heat-driven operation. This is also assumed in districtPH.

The model for heat-driven CHP plants assumes a heat generator with a certain peak capacity and certain, constant efficiencies for heating and (usually smaller) for electricity. The heat is fed into the district heating system. Once the heat generation has been calculated, depending on the load and the other available heat generators, the electricity that is produced by the CHP plant in every hour can easily be calculated. This availability is then used in the electricity balance, where it must be considered as an uncontrolled electricity production like from PV or from a wind turbine. Any excess electricity production either must be stored or is exported from the district.

One difficulty in conjunction with CHP is the allocation of the emissions and the fuel consumption, i.e. to determine the fractions relating to heat and to electricity. As long as both heat and electricity stay within the district, this is of minor importance, but as soon as part of the electricity is exported, the allocation becomes relevant. Details about the allocation method chosen for districtPH can be found in section 6.3.

6.1.6 ELECTRICITY BALANCE

Several power plants may be involved in providing the electricity supply of the district. It is therefore necessary to define a priority of these plants, with the most efficient / least polluting plants first. At any point in time, the district's electricity demand is covered by the first power plant in the priority list up to the plant's (current) capacity. If this is not sufficient, the second plant steps in, etc. By summing up the contributions over time, the annual contribution of each plant is calculated and displayed. This includes electricity that needs to be imported to or exported from the district.

From this balance, it is also possible to determine the district's degree of self-sufficiency, either on an hourly or on an annual basis – although it should be noted that the value of such indicators is questionable.

6.2 HEAT SUPPLY FOR DISTRICT HEATING

The model for conventional heat generators like coal-fired district heating plants is kept simple. All that is required are the energy carrier and its PER, PE, and CO_2 factors, the efficiency, the nominal capacity and, if applicable, the daily, weekly, and seasonal availability. Possible limitations in the ability of heat generators to quickly react to changing loads are not considered.

Two types of heat generation with higher complexity are solar thermal systems and combined heat and power plants. The corresponding models are described in more detail in the following sections.

6.2.1 SOLAR THERMAL SYSTEMS FOR DISTRICT HEATING

Apart from the number of adjustment factors and refinements, the general structure of collector equations for solar thermal collectors is as follows:

$$P = G(\tau\alpha) - U_L \Delta T$$

where

P: heat produced

G: solar radiation onto plane of collector

$(\tau\alpha)$: transmittance-absorptance product of cover and absorber

U_L: specific heat loss

ΔT: temperature difference

The equation shows that the collector can only provide heat if the solar radiation on the collector plane exceeds a certain threshold, the 'critical radiation level' required to cover the heat losses of the collector itself. This value is determined by the collector properties and the temperature difference to the surroundings, i.e. by the required supply temperature.

In central Europe the temperatures in solar DHW systems may be as low as 10 °C, which allows for relatively large fractions of the solar radiation to be harvested. District heating systems, on the contrary, are often operated at flow temperatures above 100 °C. Typical solar collectors require very high radiation levels to produce heat at this temperature level, resulting in a correspondingly low efficiency.

The widely known f-Chart method for solar DHW and solar heating systems was implemented in districtPH for the individual buildings. This method was originally developed for a typical water temperature of 20 °C. It is therefore no surprise that it turned out to be overly optimistic when calculating the solar fraction in a district heating system. Instead, a method for calculating the so-called utilizability, i.e. the useful fraction of the solar radiation on the collector plane, from [Duffie 2013] was implemented. This method accounts for the actual collector temperature and for arbitrary orientations of the collector. It requires separate calculations of the collector yield for every month and every time of the day.

For the hourly calculation of solar thermal district heating it was possible to use a suitable version of the collector equation above.

Comparing the results of the utilizability method with hourly calculations as well as with published simulation results [Schubert 2017] showed satisfactory agreement. Occasional, significant overestimations of the solar yield only occurred in connection with very low total efficiencies. With reference to the solar radiation in the collector plane, the deviations were always around a few percent.

6.2.2 COMBINED HEAT AND POWER (CHP)

As mentioned in section 6.1.5 CHP plants are considered to be heat-driven. From the capacity of the plant, it is possible to calculate the fraction of the heat demand in the district heating system that is covered by CHP. From the thermal and electrical efficiency, the available electric capacity at the respective point in time is easily determined.

6.3 ASSESSMENT

There are several options to assess the structure and amounts of energy consumption and production in a district. Examples include

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- Primary energy demand: the energy that needs to be provided at the beginning of the energy conversion chain to provide a specific service, including all losses and auxiliary energy demands during this process. Often renewable and non-renewable primary energy are distinguished.
- CO_2 equivalent emissions: Carbon dioxide is the most important greenhouse gas. The warming effects of other emissions, e.g. methane or synthetic refrigerants, can be measured in CO_2 equivalents. Burning biomass would usually not be considered to produce CO_2 because the carbon in the biomass has previously been removed from the atmosphere. In the following, like in districtPH, the abbreviated term 'CO_2 emissions' is used.
- Primary Energy Renewable: This assessment method compares different types of energy use for a fully renewable energy supply. It was developed by the Passive House Institute.
- Zero energy / energy autarky: A zero energy district would not require any energy to be imported. A more precise definition is required when energy autarky is only achieved to a certain degree, and different types of energy must be balanced.
- Net zero energy: Over the course of the year, the amount of energy produced in the district at least matches the amount of energy consumed. Often only electricity is involved in this balance. An important property of this benchmark is that energy production and consumption need not occur simultaneously; the grid is assumed to be an ideal storage. If necessary, a primary energy reference can be used to compare different energy carriers.

The results of the districtPH balance contain a breakdown of the useful, delivered, and primary energy demand of the district, including PER and CO_2 balances. Electricity imports and exports as well as possibly missing heat supply for the district heating system are summarised, too.

The Excel table allows for arbitrary other benchmarks to be implemented by the user.

6.3.1 PRIMARY ENERGY AND CO_2

Primary energy (PE) demand and CO_2 emissions are calculated from the delivered energy demand by means of conversion factors that depend on the energy carrier. The factors in designPH are the same as in the PHPP. In principle, calculating PE demand and CO_2 emissions is simple. The major difficulty is an appropriate assessment of CHP, which will be discussed in the next section.

Primary energy allows for a convenient comparison of useful energy from different sources. Usually primary energy values refer to non-renewable energy only. One of disadvantages of this indicator is that it is a moving target: In Germany, for example, with the increasing fraction of renewables in the electricity production, the primary energy factors for electricity have repeatedly been reduced during the last years.

CO_2 appears to be a particularly suitable indicator because it directly refers to the contribution to climate change.

Both indicators may lead to the conclusion that efforts for improved energy efficiency are not required as long as renewable energy is used. The fact that renewable energy uses limited resources, e.g. in competition with food production or nature conservation, is not reflected.

6.3.1.1 COMBINED HEAT AND POWER (CHP)

CHP plants simultaneously produce heat and electricity. Since they consume only one type of energy carrier there is no unique way to determine which fraction of the total energy input has to be assigned to the heat and electricity, respectively, accounting for their different value.

Heat-driven CHPs usually receive an electricity credit: If additional electricity is supplied to the grid, other power plants have to go off line. This displacement electricity is associated with a certain mixture of efficiencies and energy carriers, which are not necessarily identical with the average

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electricity mix. The primary energy and CO_2 factors of the displacement electricity mix are assigned to the electricity produced by the CHP plant. The advantage of this approach is that the primary energy and CO_2 emissions of electricity from the grid remain unchanged and can be used elsewhere without double-counting. Since the total primary energy and CO_2 emissions from the CHP are known, it is now clear which factors to assign to the heat produced in the CHP. These values can be used in the heat balance, without any further knowledge about the electricity side.

The disadvantage of this approach is that, under certain circumstances, the primary energy demand and CO_2 emissions associated with heat from the CHP can become negative (cf. the example in section 9), which seems to imply that higher heat losses of the district heating network result in lower total primary energy demand.

Nevertheless, districtPH applies this methodology as follows. Electricity from CHP is always accounted for with the displacement electricity mix. As long as it is used within the district, this is not particularly relevant: The total primary energy demand and CO_2 emissions are correct, regardless of the factors assumed for the electricity. If electricity is exported from the district, it is also accounted for with the displacement electricity mix. Consequently, the balance on the district heating side remains constant if anything changes on the electricity side, and the balance on the electricity side remains constant if additional CHP electricity is generated, but not used in the district.

Consistently, any other electricity that is exported from the district is also accounted for with the displacement electricity mix. If large amounts of renewable electricity are exported, negative PE and CO_2 factors may also result for electricity. This is again misleading: An increase in the district's electricity demand will reduce the amount of exported electricity and therefore result in a higher, albeit possibly still negative, PE demand.

This weakness of the PE and CO_2 indicators was one of the reasons for the development of the PER methodology described in the following section.

6.3.2 "PRIMARY ENERGY RENEWABLE" (PER)

The so-called PER factors (Primary Energy Renewable) were first introduced in [Feist 2014], with the purpose to serve as a suitable indicator for the sustainability of buildings from an energy standpoint. It must be recognised that renewable resources are in fact a limited resource – mainly due to space constraints and for economic reasons. The PER method intends to reflect the required renewable energy resources to cover a building's final energy demand.

6.3.2.1 PRIMARY ENERGY FACTORS FOR RENEWABLE ELECTRICITY

Renewable primary energy is energy generated from renewable resources, e.g. electricity produced by a photovoltaic system / wind turbine or heat generated with a solar thermal system. PER-factors relate the final energy demand of a building to the primary renewable resources needed to cover this demand, including distribution and storage losses. In the case of a PER-factor of e.g. 1.5, a surplus of 50% renewable primary energy is needed in order to be able to meet the final energy demand at the building. The higher the PER-factor, the higher the required resources and therefore the more important the implementation of efficiency measures in order to avoid compensation from non-renewable sources.

The PER assessment method anticipates the energy transition to 100 % primary energy supply from renewable resources. In this scenario, electricity plays a major role, generated mainly by wind turbines, photovoltaic systems and hydropower plants. The prevailing weather conditions drive all of these resources, which implies an imbalance between the times of electricity availability and electricity demand. Only a certain proportion of the generated electricity can be distributed via the mains grid, i.e. when energy demand and supply occur at the same time. A certain capacity of energy storage is inevitably required to buffer energy supply during times of surplus production to times of

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deficiency in RE supply. Various technologies are available with a comparatively high efficiency around 70-80 % as short term storage to overcome several hours or even days of energy shortcomings (e.g. pumped or other mechanical storage, batteries, thermal storage etc.). A highly promising technology for longer term seasonal storage is power to gas (PtG), where the RE electricity is converted into methane with an efficiency of typically 57 %. During times of energy demand, the gas can then either be used directly as energy carrier in the building or it can be re-converted into electricity in a Combined Cycle Gas Turbine (CCGT) plant at an efficiency of approximately 50 %. Electricity consumed at the building, which has had to undergo seasonal storage, therefore can be supplied with an overall efficiency of approx. 30 % (see Figure 7).

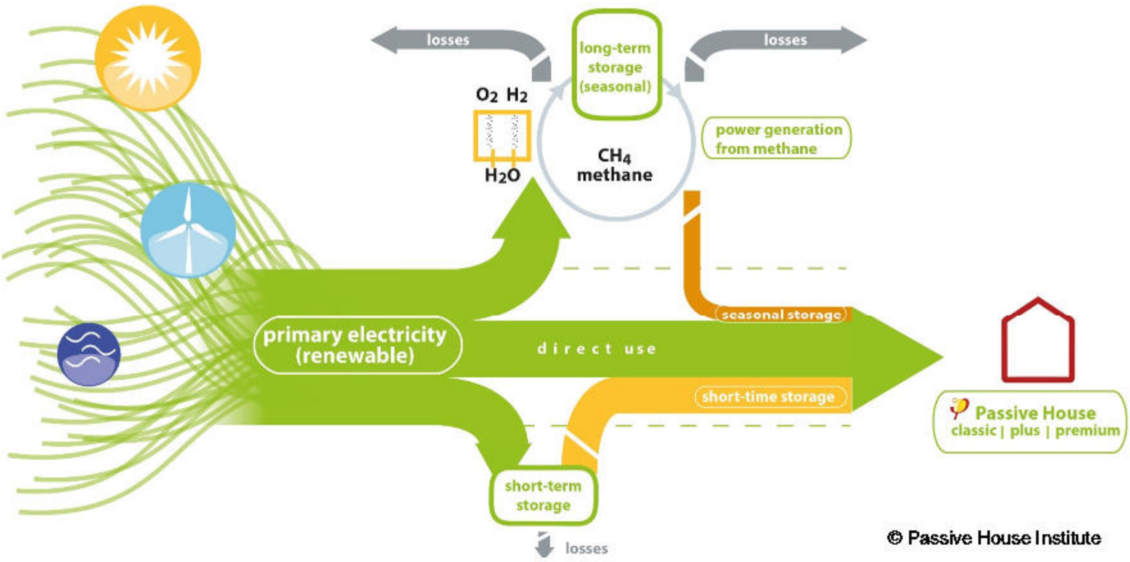

FIGURE 7. ENERGY FLOWCHART FROM THE RENEWABLE SUPPLY TO THE ENERGY CONSUMED AT THE BUILDING, INCLUDING FACILITIES FOR SHORT TERM AND SEASONAL STORAGE.

The PER factors are driven by the timely concurrence of energy supply and demand and thus the need for storage and associated losses. Consequently, the factors vary for:

- different locations, due to the different climatic conditions and thus available RE resources
- different load profiles (heating, cooling, hot water, electricity).

PER weighting factors were determined for locations worldwide by means of hourly dynamic simulations that model the energy supply and energy demand under given weather conditions and for different regionally expected load profiles. The heating demand for domestic hot water and for electricity feature fairly constant demand profiles over the course of the year, which results in PER factors of about 1.3. The demand can be covered to a large extent directly from the primary source, without the need for storage, or via efficient short term storage technologies. The energy demand for heating, on the contrary, only occurs during winter with low solar energy resources. A large part of the energy demand must therefore undergo seasonal storage, which implies high losses. As an example: For Central Europe the PER-factors for electric heating (e.g. via a heat pump) are around 1.8. This higher factor clearly indicates the increased importance of employing efficiency measures to reduce the heating demand.

6.3.2.2 ASSESSING OTHER ENERGY CARRIERS

Energy carriers other than electricity also need to be treated consistently in the PER methodology. For this purpose, each building is assigned an annual biomass budget of 20 kWh_{PER}/m^2_{TFA} with a PER factor of 1.1. This budget reflects the maximum contingent of biomass that can sustainably be used in the building sector for energy purposes, caused by limited availability of biomass worldwide and its competitiveness for other uses (food, transport sector, raw material use). This same biomass budget is credited for all buildings and all energy uses, assuming that if the biomass is not being used locally (e.g. in a wood burner or pellet furnace) it is being put to use in a centralised plant (e.g. in a CHP to provide electricity and heat for a district heating network). If the biomass used in a building exceeds the admissible budget, the respective final energy demand is rated as RE gas (RE electricity converted into methane). Applying this approach restricts the use of biomass in buildings to a certain extent, rather than enabling its use as means for carbon offsetting with inefficient solutions. The PER approach encourages solutions where the highly valuable energy carrier biomass is used in buildings only in the winter period but not during summer when there are plenty of other renewable sources readily available.

For the PER assessment of heat generated with on-site solar thermal, the system's yield is compared with the potential yield of a photovoltaic system under the same boundary conditions (size, location, orientation, shading etc.). This approach encourages small and medium sized systems, whilst penalizing large systems over-dimensioned for the on-site energy demand.

Any gas used in a building is considered RE gas. The comparatively high PER factor of 1.75 (if beyond the biomass budget) reflects the efficiency of the energy intensive conversion process from RE electricity into methane.

6.3.2.3 DISTRICT HEATING AND COMBINED HEAT AND POWER (CHP)

The PER factor of district heat, as delivered to the building, is calculated from the PER of the different heat generators that contribute to the heat supply, and from the total useful heat that is supplied after deduction of network and storage losses.

For heat from CHP plants, districtPH uses a similar methodology as the PHPP, by assigning a PER bonus to the heat that is produced in the CHP. It is assumed that there is a fully renewable electricity mix in the grid, and that any electricity which is produced by the CHP can be used in the grid.

The reference electricity generator is a combined cycle power plant, operating with gas and producing electricity with an efficiency of 55%. Contrary to the PE methodology described above, the PER factor of displacement electricity is thus close to the technical optimum, so that negative PER factors are very unlikely.

6.3.2.4 OFFSETTING ENERGY DEMAND WITH ON-SITE RENEWABLE ENERGY

Offsetting the energy demand with on-site renewable energy production is often set as a goal, leading to "net-zero" or even "plus energy" buildings. The objective is to generate at least as much energy as is being consumed – in absolute terms, i.e. MWh per year. Whilst this at a first instance appears a noble approach in terms of minimising climate impact, this approach is problematic for the following reasons:

- The effects of energy storage and distribution are neglected entirely. As indicated by the PER factors, however, the timely misbalance between demand and supply can lead to significantly higher amounts of required energy supply in order to be able to compensate for the losses and still meet the on-site final energy demand.
- It is much easier to offset the absolute energy demand in the case of a single family home than it is for a multi-storey building. Multi-story buildings, however, have a much lower impact in terms of space and material use and are therefore significantly advantageous in terms of sustainable housing developments.

Absolute off-setting is therefore misguiding in many cases and does not lead to sustainable solutions as an automatism. It is therefore important to assess the energy efficiency of a building and the associated renewable energy production independently of one another.

The same reasoning holds for a district: If electricity is produced in the district, it becomes part of the overall electricity mix in the connected grid. Even if parts of it are directly used in the district, production and consumption are counted separately.

6.3.2.5 IMPLEMENTATION OF PER ASSESSMENT

The PER assessment methodology and the calculation algorithms were mainly used as implemented in the Passive House Planning Package Version 9 [PHPP]. The PER factors form part of the PHPP climate data sets which are used for districtPH. It is thus possible to calculate each building's total final energy demand and then automatically determine the total PER-demand by weighing the final energy demand with the PER factor corresponding to the type of energy consumer and the energy carrier used.

The PER demand of the district is given as the sum of the PER demands of all buildings. No PER demand is reported for the 'other' electricity consumers, such as street lighting or electric cars. Those consumers have their own load profile, and it would be necessary to determine the corresponding PER factors by a dedicated simulation for each climate data set, which would have been beyond the scope of this project.

Renewable energy production within the district is summed up and shown separately. This applies to photovoltaics, wind energy, and solar thermal, either in central plants or on the buildings. Only primary electricity is counted here, neither fossil fuels nor biomass or renewable methane. As explained above, the PER production is not offset against the PER demand.

7. NETWORKS FOR HEAT AND ELECTRICITY

Districts are able to balance load fluctuations and therefore smooth out load peaks by drawing on electricity and heating networks. Seasonal storage devices and cogeneration systems are easier to implement on a district level. Relevant influential factors that need to be taken into account include district heating grids and their losses, the use of solar thermal energy, the utilisation of waste heat, power generation from PV and wind, possible time shifts between load profiles and the availability of renewables, and energy storage devices.

District heating and electricity networks are therefore a key component of districtPH. In this section we describe the relevant calculation and input procedures.

7.1 HEAT

7.1.1 NETWORK INPUT

District heating networks can be divided into three important components: heat generators, heat consumers, and the distribution network. Due to the relevance of distribution heat losses it was necessary to allow for a detailed input of the network sections' lengths and properties. A geometrical model is appropriate here, though for the reasons detailed in section 2.2 we did not implement an automatic GIS import routine. Instead, all data can be entered into Excel. A graphical interface allows to place heat generators, heat consumers, and network sections with their respective properties onto an aerial view of the district.

For further processing these inputs are lumped together into the relevant characteristics of the network. A single specific heat loss, combined with winter and summer water temperatures, describes the distribution losses. Each consumer is assigned to one of the building types used in the

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district, and each heat generator is of one of the types that are used in the district heating calculation.

7.1.2 CALCULATION MODEL

For the multiple calculation of scenarios over several decades, a fast, sufficiently accurate calculation method was required. The method had to be able to determine the fraction of the total heat load that is covered by each heat generator. It also had to be able to take short and long-term storages into account.

An hourly analysis was implemented to allow for detailed investigations and for comparison with simplified methods, but was carefully kept separated from the rest of the calculation model to allow for easy removal. As expected, this type of model requires unacceptably long calculation times when applied to long-term scenarios, but it can be useful for more detailed investigations of a specific state of the district.

Since the load on a district heating system depends on the weather and varies from month to month, attempts were made with a model similar to the well-proven monthly heating and cooling energy balance of EN ISO 13790. It appeared promising to treat heat gains from renewable sources, waste heat, etc. analogously to solar and internal heat gains in a building model, and to determine the fraction of this heat that can be utilised by the district via a utilisation factor based on the ratio of gains to losses and on the time constant. However, the utilisation factor was difficult to determine in general, particularly since no relationship between the time constant and the network properties could be identified. Finding adequate models for heat storages, with their non-linear behaviour (cf. section 7.1.3), was an additional challenge for this monthly approach.

Finally, a method was developed that works with representative weeks, separately for winter and summer. Loads and heat supply capacities are chosen in a way that results in correct averages over the heating and cooling period, respectively. Possible mismatches of loads and capacities as well as the load shift potential of e.g. storages are represented correctly by using typical hour-by-hour profiles. The hourly analysis also allows to consider the fluctuating nature of renewable energy sources. To account for the effects of offices and schools that are closed on weekends, for waste heat that is only available during working days, etc., there are three types of days in each season: Monday to Friday, Saturday, and Sunday. On this basis, the load, including network and storage losses, is distributed to the different heat generators.

Obviously, such an approach is less accurate during extremely cold or hot periods, on mild spring or autumn days, or around Christmas and Easter. Nevertheless, comparisons with hourly calculations – that neglect special holidays as well – resulted in an acceptable agreement.

7.1.3 STORAGES

While the assignment of heat generators to the existing loads, as described above, is comparatively straightforward, a correct description of storage effects turned out to be surprisingly complex.

The first step is to determine the storage management strategy that is to be modelled. A storage in a conventional district heating network may simply have the task to flatten out peak loads, so that the capacity of the heat generators can be reduced. However, it is evident that more sophisticated applications are useful: If a solar thermal system is present, the storage can shift the load such as to use as much solar energy as possible. With a third heat generator, e.g. a CHP plant or a biomass boiler, being more advantageous than heat generator no. 1, but less so than the solar heat, the question arises under which conditions this heat should be stored. It is desirable to make use of the relatively efficient heat generator no. 3, offsetting its limited capacity and increasing its operating hours. But storing this heat also results in additional heat losses from the storage, and it is hard to

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predict whether it would not be better to reserve part of the storage capacity for forthcoming solar energy.

Within districtPH, a simplified strategy is applied. The user determines the heat generators that are connected to the storage. Solar collectors and waste heat will be a typical choice. These heat generators first serve the network, any excess heat is fed into the storage as long as it is not fully charged.

The model contains two storages: a short term storage that is directly integrated into the hourly / weekly analysis, and a seasonal storage that can transfer heat from one season to the other. In the following, these models are explained, starting with the seasonal storage.

7.1.3.1 SEASONAL STORAGES

The method used for seasonal storages is illustrated using an example: In winter there are net heat losses in the district heating network which are, to a certain extent, covered by the storage. In summer, on the contrary, the storage is charged.

The calculation uses the following quantities and storage properties:

Q_W the heat demand of the district heating network in winter, including storage losses, MWh

$Q_{S,max}$ the maximum amount of heat that can be stored at a useful temperature level, MWh

$Q_{S,min}$ the minimum heat content of the storage, MWh. Usually, this value will be negative: if the storage temperature drops below the return temperature of the district heating network the storage still has heat losses, but it cannot provide any useful heat. Correspondingly, the storage requires the heat $Q_{s,min}$, e.g. at the beginning of the summer, before it can become effective.

Q_S the heat content of the storage, MWh, where $Q_S = 0$ is the point above which the storage can provide heat to the network

$Q_{S,0}$ the heat content of the storage at the beginning of the winter, MWh

$Q_{S,tW}$ the heat content of the storage at the end of the winter, which is defined to be the beginning of the summer, MWh

t_W the length of the winter, days

t_0 the duration between the beginning of the winter and the time when the storage is empty ($Q_S = 0$), days. This value is only relevant if it is less than t_w, i.e. if $Q_W > Q_{S,0}$.

$\dot{Q}_S$ the heat loss of the storage at the network temperature, W. The calculation is simplified by assuming that this value is constant, independent of the storage temperature.

At the beginning of the winter the storage has the content $Q_{S,0} \geq 0$. It loses heat with a power of $\dot{Q}_W = Q_W / t_W$ (> 0) until, at time t_0, the state $Q_S = 0$ is reached. Afterwards, the heat loss is only $\dot{Q}_S$ (> 0, mind that this is not the deviation with respect to time). The heat loss becomes zero when the storage content reaches $Q_{S,min}$. From these assumptions $Q_{S,tW}$, the state of the storage at the end of the winter, can be calculated.

Three cases have to be distinguished:

1) $Q_W \leq Q_{S,0}$: $Q_{S,tW} = Q_{S,0} - Q_W$. The storage is sufficiently large and, at the beginning of the winter, sufficiently charged to fully cover the heat demand in winter. In this case the state of the storage is not unique. It may be assumed that $Q_{S,0} = Q_{S,max}$ or, alternatively, $Q_{S,tW} = 0$.

2) $Q_W > Q_{S,0}$: $Q_{S,tW} = -\dot{Q}_S(t_W - t_0)$ where t_0 is initially unknown because it depends on $Q_{S,0}$

3) $Q_W > Q_{S,0}$ and $Q_{S,tW} = Q_{S,min}$. At the end of the winter, the storage is empty. The state of the storage is obviously known in this case, but it is not clear yet when this case occurs.

We consider case 2) first and assume that the storage size is unlimited in both directions. Then, due to $t_0 = Q_{S,0}/\dot{Q}_W$,

$$Q_{S,tW} = -\dot{Q}_S\left(t_W - \frac{Q_{S,0}}{\dot{Q}_W}\right)$$

During summer the storage is recharged by the (net, i.e. after covering the summer heat demand including storage losses) excess heat Q_{Summ},

$$Q_{S,0} = Q_{S,tW} + Q_{Summ}$$

provided that, as it was assumed here, the storage size is sufficient. Using this in the equation above,

$$Q_{S,tW} = -\dot{Q}_S\left(t_W - \frac{Q_{S,tW} + Q_{Summ}}{\dot{Q}_W}\right)$$

Solving for $Q_{S,tW}$,

$$Q_{S,tW} = \frac{\dot{Q}_S(Q_{Somm} - Q_W)}{\dot{Q}_W - \dot{Q}_S}$$

Introducing limitations to the storage capacity, if $Q_{S,tW} < Q_{S,min}$ the storage cannot be discharged as much as calculated above. In this case, $Q_{S,tW} = Q_{S,min}$.

From this result we can calculate $Q_{S,0}$. Corresponding to the winter period, if $Q_{S,max} < Q_{S,0}$ the storage content is limited to $Q_{S,0} = Q_{S,max}$.

The savings with reference to the net heat demand of the network (i.e. without the losses of the seasonal storage) are $Q_{S,0} - t_0\dot{Q}_S$.

The energy needed to charge the storage can be calculated as $Q_{S,0} - Q_{S,tW} + (t_{year} - t_0)\dot{Q}_S$, where t_{year} is the length of the year and t_0 is limited to t_W.

A corresponding algorithm is used if there is excess heat in winter and heat demand in summer.

In order to be able to distribute the savings, the energy demand for charging the storage, and the storage losses to the different heat generators, additional assumptions are required:

- The seasonal storage is subordinated, i.e. it provides heat only when the short term storage is empty, and it is charged only when the short term storage is full. Consequently, the load on the network, including the short term storage, remains unchanged by the seasonal storage with regard to its size and temporal distribution.
- Heat generators that are not selected to charge the seasonal storage are only turned on if the seasonal storage is empty ($Q_S \leq 0$). Until then, the seasonal storage, possibly together with the heat generators connected to it, provides the total heat load.
- The seasonal storage is charged by all heat generators that are connected to it, proportionally to their excess capacity.
- The seasonal storage does not change the loads during the season with excess heat generation.

It should be noted that, depending on the situation, better storage management strategies could be possible. For example, the heat saved in winter can be distributed reversely to the priority of the heat generators; in other words, the worst heat generator is replaced first. Similarly, the energy for charging the storage could be taken from the respective heat generators according to their priority. Both options appear to be overly optimistic because they assume that the storage operating system can tell the future: In the charging process it has to know when the second best heat generator has to start up in order to achieve just the right state of the storage at the beginning of the winter. In the discharge process it has to know how much heat would be left in the storage at the end of the winter after the worst heat generator has been replaced by heat from the storage. If, additionally, the storage losses are taken into account, the situation gets even more complicated: Now, it may or may not be advantageous to discharge the storage as fast as possible, depending on whether the reduced storage losses compensate for the reduced energy savings (or CO_2 emissions savings, or whatever quantity is to be minimized) when a better heat generator is replaced by the storage.

As long as the seasonal storage is not empty, it can not only serve as a net heat generator, but also shift loads between heat generators. If, for example, there is excess solar heat because an adequate short term storage is missing, the seasonal storage can shift this heat to periods when it is required. Thus, there are cases where the winter heat demand can be covered by more efficient heat generators as soon as the seasonal storage steps in, without it being required to transfer heat between the seasons.

After the seasonal storage has run empty in winter, the network is assumed to operate as if there was no seasonal storage.

Taking the above aspects into consideration, a somewhat complicated case-by-case analysis for the heat generators results, as described in the following table.

TYPE OF CONNECTION AND USE OF HEAT GENERATOR			CONSEQUENCES	
CONNECTED TO SHORT TERM STORAGE	CONNECTED TO SEASONAL STORAGE	FRACTION THAT IS USED IF ONLY THE SHORT TERM STORAGE IS OPERATED	ACTION BEFORE SEASONAL STORAGE IS EMPTY[1)]	AVAILABLE FOR SEASONAL STORAGE[2)]?
x		x	used with or without seasonal storage, thus not relevant for seasonal storage energy balance	no
x			not required without seasonal storage, thus not required with seasonal storage either	no
		x	may be changed due to seasonal storage, requires recalculation	no
			not required without seasonal storage, thus not required with seasonal storage either	no
	x		partly covering the remaining heat load[3)]	yes[3)]
x	x	x	used with or without seasonal storage, thus not relevant for seasonal storage energy balance	no
	x	x	partly covering the remaining heat load[3)]	no
x	x		partly covering the remaining heat load[3)]	yes[3)]

[1)] During this period the seasonal storage, in conjunction with the heat generators connected to it, is fully covering the network's heat load.

[2)] The heat generator is charging the storage in periods of excess heat availability and reducing the discharge in other periods.

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[3] If the seasonal storage is not sufficiently large to cover the load of the network for one week, it is assumed that, during the period of net heat loss, excess heat that is not used by the short term storage cannot be used by the seasonal storage either.

7.1.3.2 SHORT TERM STORAGES

The short term storage is calculated on an hour-by-hour basis. Using the above symbols and

$Q_S{}'$ the heat content of the storage at the end of the time step

$\dot{Q}_L$ the heat load of the network without storage losses

$\dot{Q}_{avail}$ total capacity of all heat generators connected to the storage

dt length of time step

the following holds for the change of the energy content in the storage, $\Delta Q_S = Q_S{}' - Q_S$, for any dt:

$\Delta Q_S = (\dot{Q}_{avail} - \dot{Q}_L - \dot{Q}_S)dt$ for $Q_S \geq 0$

$\Delta Q_S = (\dot{Q}_{avail} - \dot{Q}_L - \dot{Q}_S)dt$ for $Q_S < 0$, $\dot{Q}_{avail} - \dot{Q}_L \geq 0$

$\Delta Q_S = -\dot{Q}_S dt$ for $Q_S < 0$, $\dot{Q}_{avail} - \dot{Q}_L < 0$

From this, as long as $\dot{Q}_{avail} - \dot{Q}_L \geq 0$ it is straightforward to determine the state of the storage at the end of the time step. For $\dot{Q}_{avail} - \dot{Q}_L < 0$ a zero crossing may occur during the time step. It is necessary to determine at which time Δt this occurs:

$$\Delta t = \frac{Q_S}{\dot{Q}_L + \dot{Q}_S - \dot{Q}_{avail}}$$

Δt is then restricted to the range between zero and the length of the time step. Now, it is possible to calculate the new state of the storage as

$Q_S{}' = -\dot{Q}_S(dt - \Delta t)$ for $\dot{Q}_{avail} - \dot{Q}_L < 0$ and $0 < \Delta t < dt$

$Q_S{}' = Q_S + (\dot{Q}_{avail} - \dot{Q}_L - \dot{Q}_S)dt$ for $\dot{Q}_{avail} - \dot{Q}_L < 0$ and $\Delta t = dt$
(equivalent to $Q_S \geq 0$ during the whole time step)
and always for $\dot{Q}_{avail} - \dot{Q}_L \geq 0$

$Q_S{}' = Q_S - \dot{Q}_S dt$ for Δt = 0
(equivalent to $Q_S < 0$ during the whole time step)

$Q_S{}'$ is then restricted to the range between $Q_{S,min}$ and $Q_{S,max}$.

From the state of the storage before and after the time step the useful heat provided by the storage $Q_{S,useful}$ can be calculated:

$Q_{S,useful} = Q_S - \dot{Q}_S \Delta t$ for $0 < \Delta t < dt$

$Q_{S,useful} = \max(0, Q_S - Q_S' - \dot{Q}_S dt)$ for Δt = 1
(equivalent to $Q_S \geq 0$ during the whole time step)

$Q_{S,useful} = 0$ for Δt = 0
(equivalent to $Q_S < 0$ during the whole time step)
and always for $\dot{Q}_{avail} - \dot{Q}_L \geq 0$

Mind that, due to storage losses, the amount of heat that is supplied to the storage is possibly different from $Q_{S,useful}$.

The amount of heat that needs to be supplied by the remaining heat generators $Q_{S,rest}$ can then be calculated as

$$Q_{S,rest} = \max(0, Q_L - Q_{Solar} - Q_{S,useful})$$

The fraction $Q_{avail,used}$ of the available heat that is actually used by the network, including the storage losses, is

$$Q_{avail,used} = Q_{avail} \qquad \text{for } Q_{S,rest} > 0$$

$$Q_{avail,used} = \dot{Q}_L dt + \dot{Q}_S dt + \Delta Q_S \qquad \text{otherwise}$$

Now both the heat supplied by the storage and the additional heat to be generated to cover the storage losses can be calculated if the state at the beginning of the time step is known.

The latter is not always the case: Since the storage model is non-linear it is impossible to calculate the inital state based on an energy balance over the whole week. Iteration, i.e. running the model again and again until the state of the storage at the beginning of the week is identical to the state at the end of the week also turned out to be impractical: Cases can be found where it takes years for the storage to reach a quasi-steady state.

Finally an approximate solution was applied: By using the algorithms for the seasonal storage from section 7.1.3.1 for the typical week, a first estimate of the inital conditions is found. Starting from this point, the typical week is calculated twice, with the first week used for better determining the initial state, and the second week evaluated as the basis for the following calculations.

7.1.3.3 STORAGES IN THE HOURLY BALANCE

For the more detailed hour-by-hour simulation it is easy to determine the state of the storage in hour *n* if the state in hour *n*-1 is known. The model from section 7.1.3.2 was used here for both the short term and the seasonal storage.

It turned out once more that the determination of the initial state was not trivial, particularly for larger storages. In an annual simulation, successive iterations are prohibitively time-consuming.

Therefore, an approximate solution similar to the above was applied: A preliminary calculation that uses an annual energy balance similar to section 7.1.3.1 is carried out to determine the state of the storage at that time when, from experience, the storage is the farthest discharged. This time was chosen to be April 1. It will happen regularly that the state of the storage shows a discontinuity at this time. Accordingly, the energy transferred into or out of the storage in the respective hour cannot be determined and was set to zero. Since only one hour of the year is affected by this simplification, its effect for the final result is negligible.

7.2 ELECTRICITY

The calculation of the electricity grid is, to a large extent, similar to the calculation of the district heating network.

7.2.1 CALCULATION

To provide suitable input data for the hourly calculation it is appropriate to distinguish between different types of electricity consumption:

- heating, either direct-electric or via heat pump
- DHW
- cooling
- household and other electricity in winter
- ditto in summer

For the calculation of typical weeks, the heating demand is assumed to occur in the winter period, the cooling demand occurs in the summer period, DHW demand is constant over the year, and other electricity demand may vary between winter and summer seasons (e.g. in swimming pools or supermarkets). The load profiles for heating, cooling and DHW are carried over from the district heating inputs.

The hourly calculation works similarly to the corresponding procedure for district heating, making use of the monthly energy demands for heating and cooling as well as of the daily profiles for all loads.

7.2.2 STORAGES

Electricity storages are treated in a similar way as heat storages for district heating (cf. section 7.1.3). The difference is that there is no non-usable fraction of the storage; instead, additional losses may occur during charging and/or discharging of the storage.

This represents the typical behaviour of batteries, pumped-storage hydro or pressurized air storages, where internal resistances or conversion losses result in a reduction of storage efficiency.

8. PUBLIC CONSUMERS AND TRAFFIC

8.1 STREET LIGHTING

Street lighting makes up a relatively small fraction of the total electricity consumption in a district. Usually its consumption is on the order of a few percent of the household electricity consumption.

However, street lighting is a public consumer that is run by the city, and its electricity consumption can be influenced to a relatively large extent:

- modern LED lighting allows for slightly higher efficiency than conventional lamps; in addition, LED lighting can better be focused to those parts of the street where light is required
- control systems can reduce the electricity demand further, particularly in less frequented areas

An auxiliary calculation was set up to determine and check the electricity consumption of street lighting in the district. To represent control systems a simple model was developed that runs a user-determined fraction of the lamps for one hour before sunrise and for two hours after sunset only.

8.2 ELECTRIC RAIL TRANSPORT

Trams or electrical rapid transit systems are usually run with electricity, but of a different type than the AC electricity used in households. Direct current with voltages of 500 to 750 V is typical, and the production (or transformation) of this electricity usually takes place in a central location. Nevertheless, such a transformer station may be located within the district in question. Therefore, a corresponding consumer was implemented.

Daily load profiles of the electricity consumption or standard load profiles were not available. The electricity consumption of a tram or underground train does not depend on the number of passengers very much. Therefore typical load profiles could be estimated from timetables in medium-sizes cities, showing the distribution of the electricity consumption to different times of the day and days of the week.

Battery-operated electric busses are still an emerging technology. They may either be charged within a few hours during the night, or intermittently during operation, either at the terminal stops or at additional stops in between. Predictions which technology will be successful are not possible yet. What can be said is that the electricity consumption of an electric bus is on the same order of magnitude as for electric light rail or metro systems.

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8.3 ELECTRIC PASSENGER CARS

The term 'electric mobility' can relate to different types of individual transport. Electrically supported bicycles have a negligible electricity consumption of approximately 1 kWh per 100 km. Therefore, although they may possibly make up a considerable fraction of future urban transportation, they are not explicitly accounted for in districtPH.

Electric passenger vehicles, or battery electric cars, have higher electricity consumptions of about 20 to 25 kWh per 100 km, including air-conditioning, lighting, electronics, etc., and the average distances travelled will be much bigger. This type of vehicles is also considered in districtPH.

Interestingly, even a total change from fossil fuels to electric vehicles will only lead to a moderate increase of the total electricity consumption. In Germany, this increase is estimated to be approximately 20% ([BMU]).

Using the annual kilometers travelled, the rate of car ownership and the fraction of electric vehicles, districtPH can easily calculate the electricity demand of electric cars. The load profile of this future technology is more difficult to determine. Two extreme scenarios appear possible: In the first case the vehicles are being fully charged whenever possible, so that they are immediately available to their owners should the need occur. This means that the residents of the district will start charging their vehicles as soon as they come home in the afternoon. Typical charging periods may last for 1 to 4 hours. A corresponding load profile was provided as a default.

In the second case the batteries will have a capacity that is significantly higher than the average daily electricity consumption, in order to provide sufficient capacity also for long-distance travels. Furthermore, appropriate demand response mechanisms can be implemented, particularly variable electricity tariffs that depend on the availability of renewables, known for a few days beforehand. With a suitable infrastructure, the electric load then has a potential of being shifted for more than one day.

Users of districtPH may choose between two options for electric cars: Either the above-mentioned load profile is used or charging electricity is considered to be flexible within one day. The fraction of electric cars that uses either option is user-defined.

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9. EXAMPLE APPLICATION

In this section, a simple example will be laid out in order to illustrate potential uses of districtPH which are relevant to general interest. This example was also used for the presentation of districtPH on the 22nd International Passive House Conference in Munich [Schnieders 2018a].

A small district in the north of Darmstadt, Germany, was selected to be used as an example (Figure 8). The district covers an area of about 350 x 350 m. The railway line and the ring road on the western side are separated by a landscaped noise barrier approximately 20 m high.

In total, 63,000 m² of living area were included in the calculation. The district is primarily populated with terraced housing and 3 and 4 storey multi-family houses. The areas of the terraced house plots range from 200 to 400 m². For the most part, the district was developed between 1995 and 2005, and any older properties are only found on the eastern edge. There is a supermarket in the south of the district and a retirement home in the north-east corner of the area selected. A natural gas network has been laid in the district, but district heating is not yet available. In the model, it was assumed that the heating and hot water requirements of all the buildings would be covered by natural gas in 2018, the first year of the simulation.

FIGURE 8. SATELLITE PICTURE OF THE EXAMPLE DISTRICT

9.1 DIFFERENT RETROFIT STRATEGIES

Using districtPH, the effects of average quality retrofits and of the possibly resulting lock-in-effect on the total CO_2 emissions were investigated. Simultaneously, the importance of the retrofit rate was examined.

The following 4 variants were considered:

- A) Retrofitting the wall, roof, floor slab and windows to the current minimum legal standard required in Germany according to the EnEV (roof 0.24, basement ceiling 0.30, exterior wall 0.24, window 1.3 W/(m²K)), and only if the building component in question is being retrofitted anyway. Window ventilation as before.

- B) Identical to A) but with the modernisation rate roughly doubled until 2028. This is realized by a shortened service life. We have therefore taken a realistic approach and assumed that primarily older building components will be modernised.
- C) Retrofitting the wall, roof, floor slab and windows as cost effectively as possible. This generally means using components of Passive House quality. The retrofit however is carried out only at the end of the service life of the building component in question. This follows a step-by-step retrofit in accordance with an EnerPHit Retrofit Plan. Installing a mechanical ventilation system with a highly efficient heat recovery system and improvements to the airtightness to EnerPHit level, as well as replacing the windows.
- D) The same as B) for the first 10 years, and thereafter, the same as C).

Figure 9 and Figure 10 illustrate the resultant CO_2 emissions for space heating and hot water production (the power consumption is initially not taken into consideration here). It should first be noted that even after 50 years, only moderate reductions in emissions were achieved in the variant A).

If the rate – but not the quality – of modernisation is increased in the variant B), this initially reduces the CO_2 emissions to a significant degree. The economic cost of this would, however, probably be considerable as purely energetic modernisations, which are not incorporated in the regular maintenance cycle, tend not to be financially viable. Sufficient funding would therefore have to be available to bring forward retrofits that were not due until a later date. In addition, manufacturers and tradespeople would have to build up the required capacities (which would then have to be run down again). If, as assumed in the example, the funding were to come to an end after 10 years, then – as shown in the graph – basically nothing more would be done in the following 10 years because all the building components (apart from the insulation level) would then be in relatively good condition. After this, further improvements would have to take place, so that in the long term the emissions are approximately equal to those in the variant A).

In variant C), the drop in emissions is initially very slow. This is partly due to the relatively new fabric of the buildings in the district used in the study. Subsequently, however, a strong, continuous and sustainable improvement can be seen.

Variant D) shows the outcome if this course of action is not taken until a later date, for example after 10 years of widespread intensive funding of broadly average quality. As in variant B), there is a longer pause after the end of the funding before the emissions resume a course similar to the variant C). However, the variant D) will not attain the final result of the systematic EnerPHit retrofit C) by the end of the 50-year financing period, whereby many opportunities will have been missed.

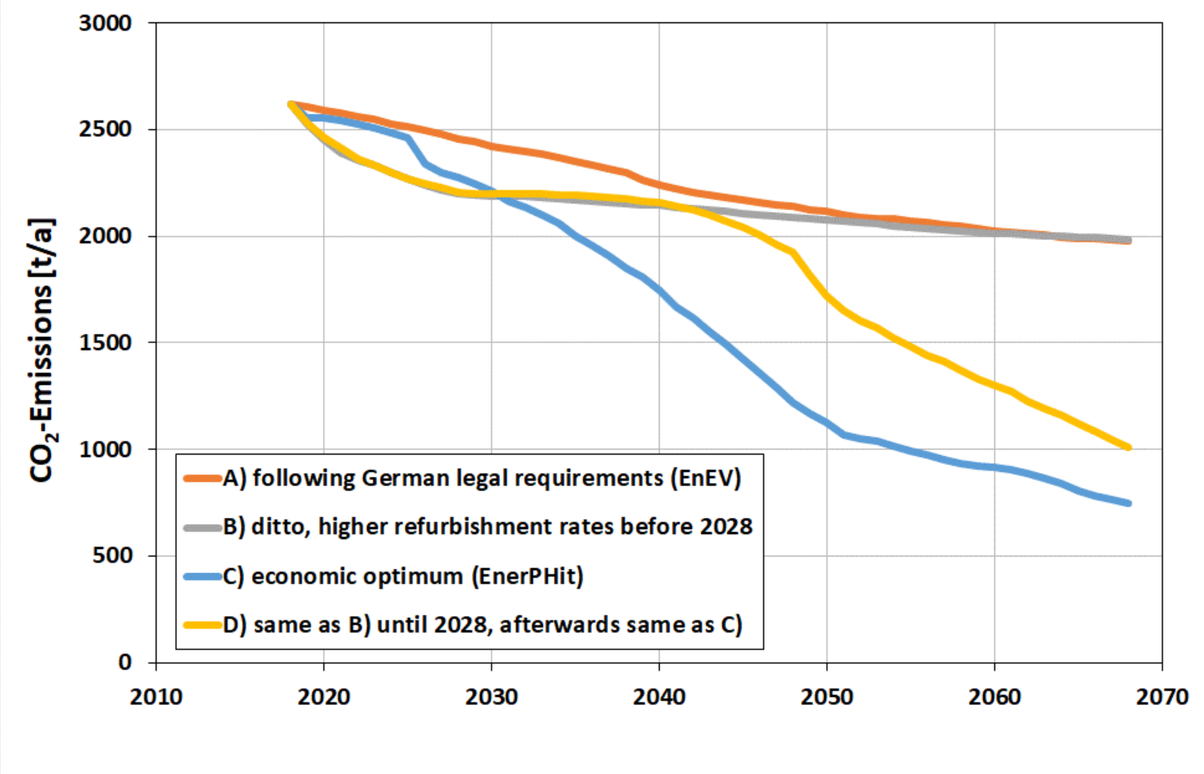

FIGURE 9. TIMELINE OF THE ANNUAL CO_2 EMISSIONS IN 4 DIFFERENT SCENARIOS

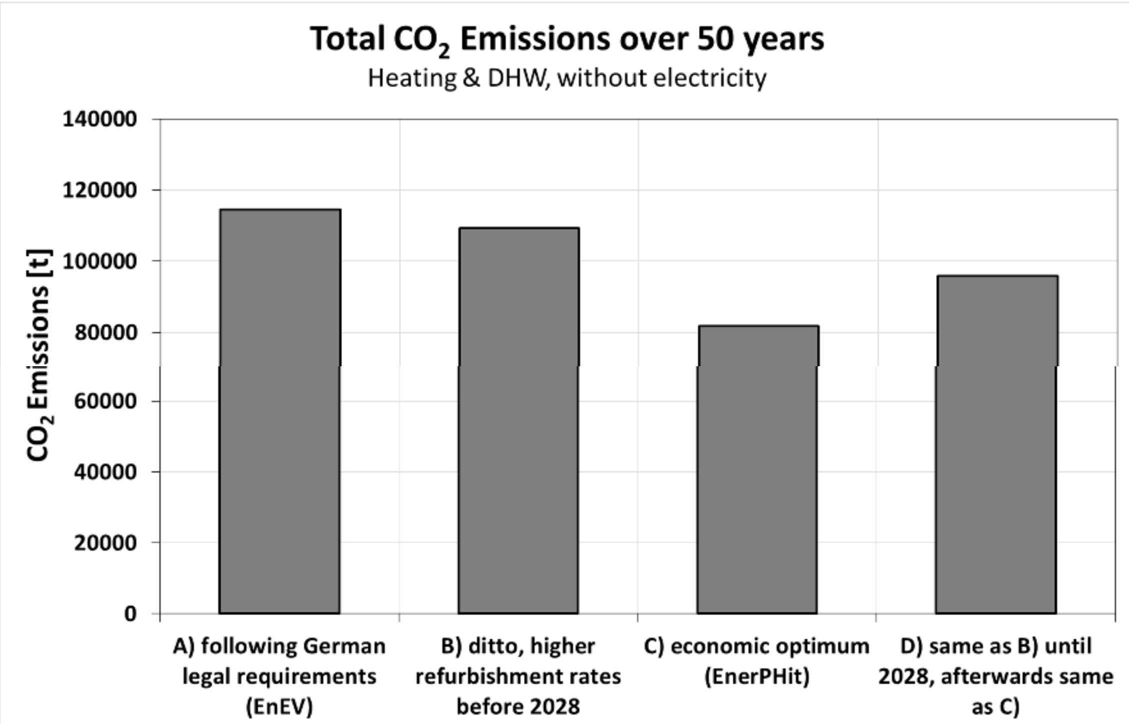

FIGURE 10. IN VIEW OF THE SUM TOTAL OVER 50 YEARS, THE LOWEST CO_2 EMISSIONS ARE ACHIEVED THROUGH CONSISTENT ENERPHIT RETROFITTING AS PART OF THE MAINTENANCE CYCLE.

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On the basis of these findings, the following conclusions may be drawn: Substantial improvements to the fabric of the building which bring it to a sustainable level are crucial for reducing energy consumption in the building sector in the long term. In contrast, funding for average quality retrofits only provides short term improvements, before having a negative impact on the starting situation for any additional measures required.

9.2 DISTRICT HEATING FOR DEEP RETROFITS

A second topic was the extent to which district heating is still worthwhile if the district is, in the long term, retrofitted to the EnerPHit level.

In the calculation, the area will now be provided with a district heating grid at usual operating temperatures (110°C for winter and 80°C for summer) (Figure 11). The heat is predominantly generated by a gas-driven CHP plant located near the supermarket with an overall efficiency of 85% (55% thermal and 30% electrical). The CHP plant is heat-driven and is designed to operate at a thermal output of 3.3 MW so that it generates approximately 3,000 full-load hours in the initial state of the district.

The heat supply is supplemented by a 2,000 m^2 solar thermal collector which can be installed on the railway line side of the landscaped noise barrier without incurring a significant adverse effect on its functionality. The collector is oriented towards the west and is inclined at an angle of 45°. It is supplemented by a storage device which operates during the day and enables the yields to be fully utilised even in summer.

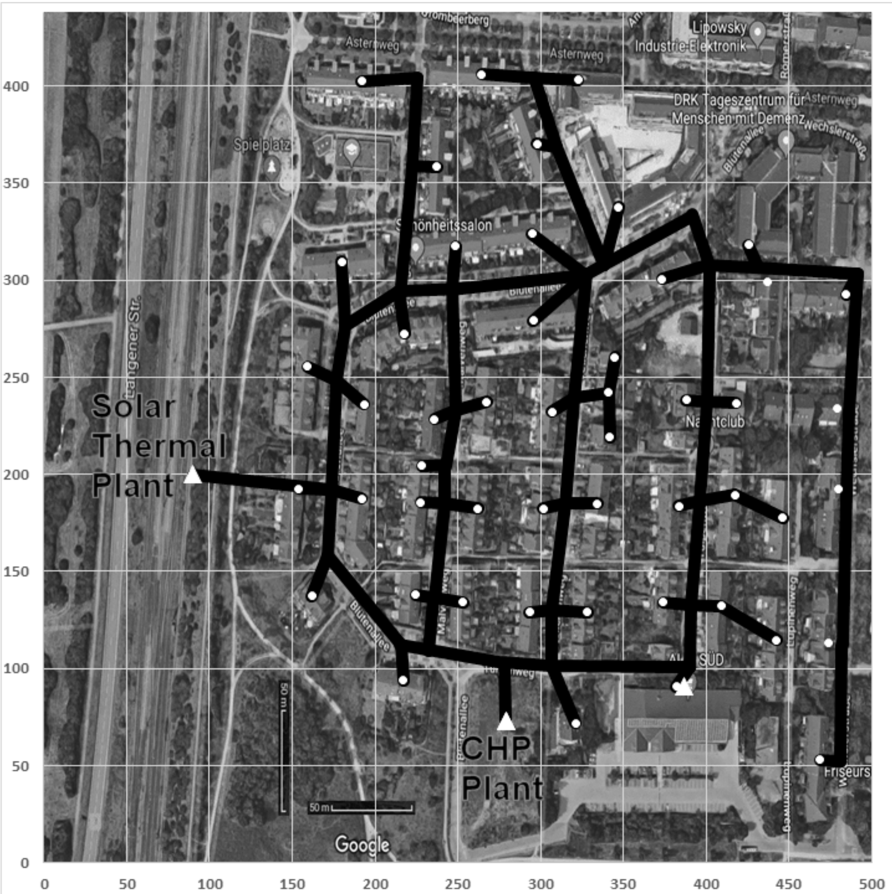

FIGURE 11. SIMPLIFIED OVERVIEW OF THE DISTRICT HEATING GRID. IT WAS ASSUMED THAT EVERY RESIDENTIAL UNIT IN THE ROWS OF TERRACED HOUSING WOULD REQUIRE ITS OWN CONNECTION TO THE DISTRICT HEATING TRANSMISSION LINE.

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The refrigeration units in supermarkets consume large amounts of electricity. In winter, the ideal use for the waste heat generated is to directly heat the supermarket. In summer, however, the waste heat can be used in the district heating network, but it must be passed through a heat pump to bring it to the corresponding temperature. A usable waste heat output of 57 kW was set during opening hours and 33 kW for other times.

At the starting point, the district heating grid incurred heat losses of 17% of the heat fed in. In summer, the solar thermal collector and supermarket approximately cover the heat losses of the network. Setting up a district heating grid would reduce the total CO_2 emissions of the district (for heating, hot water and all electricity consumers) from 5,100 to -2,100 t/a. The emissions are counted as negative due to the CO_2 credit for the surplus power (cf. section 6.3.1.1). In Germany, renewable electricity is not replaced in the overall electricity mix (power grid operators prioritise purchasing electricity from renewable sources), instead it replaces the electricity which is generated by inefficient, coal-fired medium-load power stations. The corresponding CO_2 factor amounts to 1,008 g/kWh. The gas CHP plant emits just 833 g per kWh of electricity, thereby simultaneously covering another portion of the thermal demand in the district.

The CO_2 emissions calculated in this way are clearly misleading, not only because higher losses from the district heating pipelines would further reduce the emissions in terms of numbers, but also because the displacement electricity mix will drastically change over the decades, the latter being the relevant timescale for buildings and building modernisations. Germany has undertaken to reduce greenhouse gas emissions by 80% to 95% compared with 1990 by as early as 2050. This can only be achieved if coal-fired power stations are largely phased out.

One possibility for a more meaningful basis of assessment, especially for long term developments, is to use the PER system (cf. section 6.3.2). The PER demand of all the buildings in the district amounts to 21,100 MWh/a in the initial state. The transition to district heating would reduce the PER demand, though only to 17,600 MWh/a.

If the complete fabric of the buildings in the district were brought up to the EnerPHit level, the PER demand would fall to 7,700 MWh/a if the gas boiler continued in operation, however it would only fall to 8,000 MWh/a if the district heating system were used. The district heating grid losses would increase to 38% of the heat fed in. The CHP plant would then be operated at only 1,200 full load hours per year.

It can therefore be seen that the installation of a conventional district heating grid for the district investigated is not advisable, neither economically nor in terms of the cost of the energy supply. The heat fed in by the large solar thermal collector (11% contribution in the EnerPHit variant) and the supermarket’s utilisation of waste heat (3%) does not affect this assessment. Heating by gas would also be questionable in a renewable energy system. As it takes considerable effort to produce gas from renewable electricity, it is more beneficial to produce heating and hot water using efficient heat pumps: the PER demand then falls to 4,300 MWh/a. This outcome however cannot be applied universally, as CHP plants with greater electrical efficiency and greater structural density can generate different results.

10. APPENDIX 1: DISTRICTPH MANUAL

The manual of districtPH can be found in the attached file

- districtPH-Manual.pdf

11. APPENDIX 2: EFFECTIVE ROOM TEMPERATURES

Summaries of the work that was carried out with respect to equivalent indoor reference temperatures, used in order to achieve more reliable calculation results for heating and cooling demand, can be found in the attached files

- Ahn_Different occupant scenarios.pdf

- Schnieders_Room_Temperatures_22_Passive_House_Conference.pdf

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Annex: DOCUMENT INFORMATION

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DOCUMENT		
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DUE DATE OF DELIVERABLE:	30 June 2018	
ACTUAL SUBMISSION DATE:	28 June 2018	
EDITORS:		
AUTHORS:	Jürgen Schnieders	
REVIEWERS:	Laszlo Lepp	
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WORK PACKAGE NO.:	4	
WORK PACKAGE TITLE:	Integrated refurbishment processes coupling building, electricity grids and heat/cold networks	
WORK PACKAGE LEADER:	SP	
WORK PACKAGE PARTICIPANTS:	SP, IKB, NHT, UIBK, Comune di Bolzano, EURAC, IPES, SEL SPA, CASA CLIMA, PASSIVE HOUSE INSTITUTE, ALFA LAVAL CORPORATE	
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