D4.1 Energy Planning Guideline for GBNs (I)

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DEFINITIONS

A Green Building (GB) (new or retrofit) is a building that, in its design, construction and operation, reduces or eliminates negative impacts, and can create positive impacts, on the climate, social, and natural environment. GBs preserve precious natural resources and improve quality of life (World Green Building Council 2022). Specifically, this means that GBs should be very energy efficient, use extensively the potential of locally available renewable energy, use sustainable materials, and aim for a low environmental impact over the entire life cycle. GBs offer their users and residents a healthy climate and a high quality of stay, they are resilient e.g., to environmental change and contribute to social inclusion.

Green Neighbourhoods aligned with the European Green Deal (European Commission 2019), is a set of buildings over a delimited area, at a scale that is smaller than a district, with potential synergies, in particular in the area of energy. A green neighbourhood is a neighbourhood that allows for environmentally friendly, sustainable patterns and behaviours to flourish e.g., bioclimatic architecture, renewable energy, soft and zero-emission mobility etc. Green neighbourhoods are the building blocks of Positive Energy Districts (PEDs) by implementing key elements of PED energy systems (Working Group on SET-Plan Action 3.2 2018). For example, the exchange of energy between buildings increases the share of local self-supply with climate-neutral energy and system efficiency. They also provide the technical conditions to enable Citizen Energy (Directive (EU) 2019/944) and Renewable Energy Communities (Directive (EU) 2018/2001) to be implemented.

Green Buildings and Neighbourhoods (GBN) in PROBONO are GBs integrated at delimited area or district level with green energy and green mobility management and appropriate infrastructure supported by policies, investments and stakeholders' engagement and behaviours that ensures just transition that maximise the economic and social cobenefits considering a district profile (population size, socio-economic structure, and geographical and climate characteristics). Delivered in the right way, GBN infrastructure is a key enabler of inclusive growth, can improve the accessibility of housing and amenities, reduce poverty and inequality, widen access to jobs and education, make communities more resilient to climate change, and promote public health and wellbeing.

DGNB certification serves as a quality stamp ensuring the state of the building for buyers. The Green Building Council Denmark (2010) established the German certification. DGNB meaning 'German Society for Sustainable Buildings'. The Danish version of DGNB was created to obtain a common definition of what sustainability is towards and making it measurable. A consortium of experts was established from all parts of the construction sector. DGNB had to be reshaped for the Danish standards, practice, traditions, and laws but is now available to certify any construction project. They chose DGNB as an innovation-forward and sustainable future guarantee. DGNB diversifies itself by focusing on sustainability and not just the environment. DGNB creates a standardised framework for the construction operations conditions and creates a common language which facilitates communication between professions and helps organize and prioritize the efforts in long and complicated development phases.

Life cycle assessment (LCA) is a tool used for the systematic quantitative assessment of each material used, energy flows and environmental impacts of products or processes (Gervasio and Dimova 2018). LCA assesses various aspects associated with development of a product and its potential impact throughout a product's life (i.e., cradle to grave) from raw material acquisition, processing, manufacturing, use and finally its disposal. In PROBONO, LCA represents the statement of a building's total energy, resource consumption and environmental impact in the manufacture, transport, and replacement of materials and for its operation over its expected life. Social life cycle assessment (S-LCA) is a method to assess the social and sociological aspects of products, their actual and potential positive as well as negative impacts along the life cycle (UN environment programme 2022). Life-cycle costing (LCC) considers all the costs incurred during the lifetime of the product, work, or service (European Commission 2022b).

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Abbreviations and Acronyms

Acronym	Description
CHP	Combined heat and power
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)
GBN	Green buildings neighbourhood
KomMod	Urban energy system modelling tool
RES	Renewable energy sources

Executive summary

Green Buildings Neighbourhoods (GBNs) want to achieve at neighbourhood level what the European Union wants to achieve at European level, they want to become climate neutral. This requires an energy system that uses only renewable energy sources (RES), including waste heat. The greatest RE potential lies in solar and wind energy. Both are fluctuating energy sources and require sufficient land for the installation of the corresponding solar and wind power plants. It follows that the energy system must be efficient and use energy sparingly, that the heating, cooling and mobility sectors must be electrified to a much greater extent and that all sectors must be linked more closely than before, and that the energy system must become smart with sufficient storage capacities, controllable loads and intelligent control combined with new business models.

Systematic energy system planning is needed to develop and implement such sustainable, climate-neutral energy systems at European, national, regional, municipal and neighbourhood levels. This report describes the typical energy system planning procedure for the development of Green Building Neighbourhoods (GBNs), which is used to determine the optimal energy system design to achieve climate neutrality of the GBN. As full supply of renewable energy generated within the GBN is usually not possible, import of carbon neutral energy is allowed under the condition that the local RE potentials within the GBN are largely exploited.

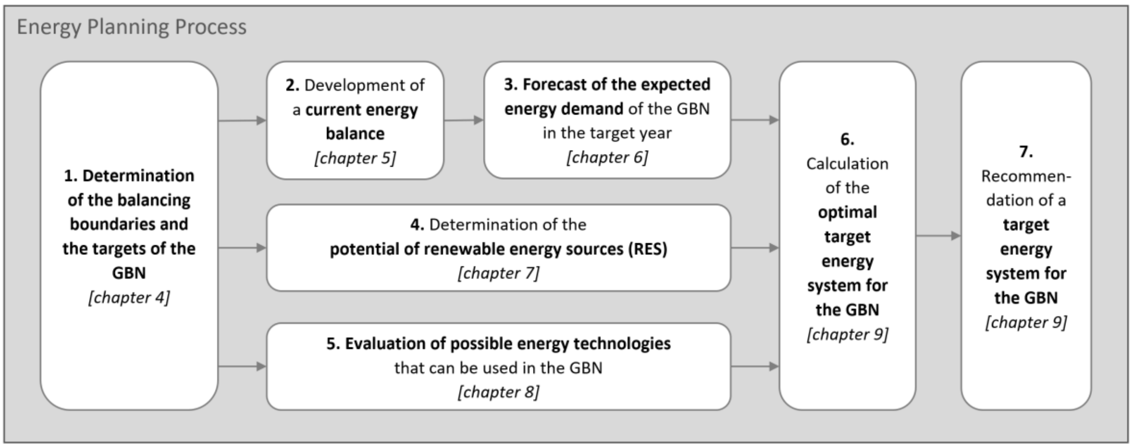

Figure 1: Process of energy planning for GBNs step by step, described in this document (with links to the chapters, which describe the steps)

This document describes the general procedure for energy planning for GBNs in 7 steps (see also Figure 1 and the references to the chapters where the steps are described). In step 1, the key data for the energy planning of the GBN must be defined, especially which area and which buildings, but also which energy sectors are considered in the balancing. On this basis, in step 2, an inventory analysis of the energy system is carried out for existing neighbourhoods that are to be converted into a GBN. On this basis, a forecast for the expected energy demand of the GBN in the target year of climate neutrality is made in step 3. In new neighbourhoods, this forecast is determined on the basis of the planning. In step 4, the potentials of available renewable energy sources within the GBN area are determined. The RE potentials in the region around the GBN are also determined, as far as they can be considered for possible import into the GBN. In step 5, the available energy technologies with their expected future costs and efficiencies are identified. The results of steps 3-5 serve as input data for the optimisation calculations, which are carried out in step 6 with an energy system modelling tool. In step 7, the input data and assumptions can be changed, and variant analyses can be carried out to adapt the energy system to the specific wishes and requirements. From this, a recommended energy system design is derived with information on the capacities to be installed for the individual energy generation plants as well as the energy converters and storage facilities. As a result, there is also data on the amounts of energy generated per energy source, the share of energy self-sufficiency of the GBN and the costs of the energy system.

With this approach, a sound energy system design for the GBNs is thus developed, which takes into account the special requirements of the GBNs (climate neutrality, high self-sufficiency share, etc.) and the characteristics of future energy systems (fluctuating, decentralised renewable energy sources, sector coupling, storage, intelligent energy management, etc.), while being cost-optimal and supply-secure.

The method described here will be applied to the Living Labs in the next step. The calculation results are described in Deliverable D4.2.

1 Introduction

1.1 Mapping PROBONO Outputs

Purpose of this section is to map PROBONO's GA commitments, both within the formal Deliverable and Task description, against the project's respective outputs and work performed.

GA Compo-nent Title	GA Component Outline	Respe ctive Chapt er(s)	Justification
TASKS			
T4.1 Climate neutral energy system planning and design methodology	T4.1 actions Demonstration and qualification of the planning software KomMod for sector-coupled (electricity, heating, cooling, mobility) and temporally high-resolution energy system optimization of the GBNs (from TRL 6 to TRL 8) (M40). Calculation of climate-neutral energy systems for all GBN LLs including innovative energy components for cost optimised. implementation of the LLs (M24). Quantification of the flexibilities that the GBNs can provide to the energy system. Cross-comparison of LL results to validate the planning software. Development of a guideline for planning climate neutral GBNs (M36).	GA Chapter 2 and Annexes I-V	This document (D4.1) is the first energy planning guideline document that describes the methodology and approach of energy planning for GBNs in general. The subsequent documents (D4.2, D4.3) will contain the applications of the methodology to LLs and a revision with recommendations based on experience.
DELIVERABLE			
D4.1 Energy Planning Guideline for GBNs (I) This report formulates the general methodology as basis for executing the energy planning within T4.1			

Table 1: Adherence to PROBONO's GA Deliverable & Tasks Descriptions

1.2 Purpose and scope of the document

This document "D4.1 Energy Planning Guideline (I)" is the first energy planning document within PROBONO. It describes the basic task of energy planning as well as the general methodology and procedure for the energy planning of GBNs.

The aim is to sensitise all stakeholders to the challenges of energy planning for sustainable, climate-neutral GBNs and to make clear which aspects need to be taken into account. For this purpose, all steps of energy planning are presented and described in general terms.

1.3 Structure of the document and its relationship with other WPS/Deliverables

The document describes the general energy planning for GBNs. Chapter 2 presents the general objectives and challenges of energy planning. It describes how, due to the ambitious objectives of sustainable energy systems, different target dimensions and the increasing complexity of energy systems, energy planning processes need to evolve. Chapter 3 provides an overview of the steps in energy planning for GBNs. These are then described and explained individually in Chapters 4 - 9. Chapter 10 concludes the document with the Conclusions.

In the following document D4.2 (Energy Planning Guideline (2)), the application of the methodology to the individual Living Labs will be described and the results of the energy planning are presented. Document D4.3 will review the Energy Planning Guidelines based on the findings of the PROBONO project and the planning processes carried out, and recommendations for energy planning for GBNs will be provided.

Energy planning in T4.1 supports the development and implementation of the Living Labs in WP 7. Energy system calculations are carried out for the LLs. The results of energy planning can also be used in WP 5 (Digitisation) as target data for the targeted energy systems. Also in WP 6, which uses KPIs to monitor implementation, the results of energy planning can be used as comparative data for the measured values of the KPIs.

1.4 Contribution to creating GBN

Climate neutrality is a fundamental characteristic of Green Building Neighbourhoods. This requires a climate-neutral energy supply with renewable energies and, if available, waste heat. In doing so, the GBN should be as efficient as possible and generate as much renewable energy as possible on site.

Under these conditions, an optimal, secure, and cost-efficient energy supply for a GBN can only be determined through sound and holistic energy planning. Thus, this is fundamental for a successful development and implementation of GBNs.

2 Objectives and challenges of energy planning

Energy planning is used to identify the configuration of the energy system that best meets the objectives and targets for the energy system.

An energy system includes all technical subsystems and components of a system that generates, imports and exports, distributes, converts, stores, and consumes energy, as well as the facilities that control the energy system. Also included are the energy carriers that transport the energy such as electricity, heat carrier media (mostly water), gases, liquid fuels (e.g., petrol or e-fuels) and solid fuels (e.g., wood or waste).

Physically, energy cannot be produced and consumed. In everyday language, generation means that energy is converted into a usable form of energy (e.g., the chemical energy contained in wood is converted into heat when burned, or solar radiation is converted into electricity in solar cells). Energy consumption means that the energy is no longer available in the energy system after it has been used (e.g., the heat used to heat a room cools down on the outside walls, warming the ambient air, and is no longer usable in the system).

The objectives for the configuration of an energy system can be manifold. There is usually consensus on the following **basic objectives of the energy policy triangle**
(see e.g. (Tagliapietra 2021)):

- **Security of supply**: the energy requirements are to be securely covered at all times
- **Economical**: the energy supply should be as cost-effective as possible (and thus "energy poverty" should be avoided)
- **Ecological**: the energy supply should be sustainable and have little or no impact on the environment and on the living conditions of all living creatures.

The basic objectives are now defined in different ways, especially since they are sometimes in competition with each other (e.g., often the cheapest energy source such as coal is also the most environmentally damaging).

Examples for the specification of energy objectives are:

- **Security of supply: The aim can be energy self-sufficiency** (supply only from own energy sources) or limiting the import of energy exclusively from very secure sources.
  Most countries and especially cities, districts and buildings are dependent on energy imports. How quickly the assessment of the security of an import source can change was

shown by Russia's war against Ukraine, which resulted in Russian natural gas no longer being available. An energy supply is only completely secure if it is based on non-finite, i.e., renewable energy sources and the energy system has secure access to the use of these renewable energy sources.

- **Economic: The aim is to achieve affordable energy costs for all residents and users of the energy system** because this is a prerequisite for positive economic development, comfortable living conditions, and participation in social life. Many energy consumers have little control over their energy costs; if they are tenants in a building without thermal insulation, for example, their heating bill can be high even if they heat their homes sparingly. Efficient energy use and a high proportion of locally generated renewable energy can significantly reduce the risk of future energy cost increases and energy poverty.
  The costs of energy supply are essentially determined by the costs of importing energy sources, the components of the energy system and the amount of energy required, which depends on the costs of energy efficiency measures (e.g., thermal insulation of buildings). It must be taken into account that energy prices are not only determined by the costs of extracting the energy sources, but also strongly influenced on the world market by shortages and the policies of the supplier countries, as well as by taxes and levies. The demand for affordable energy costs refers to the end consumers, whose energy prices are determined by energy policy but also by the necessary energy systems to provide energy. For example, the generation of solar power costs about 10 €ct per kWh in Europe and only about 5 €ct per kWh in large-scale systems in sunny parts of the world, making it one of the cheapest energy sources worldwide (IRENA 2022). In comparison, the electricity purchase costs for households, for example, are significantly higher on average in Europe at 25 €ct/kWh (European Commission 2022a). However, the use of solar energy on a large scale requires a transformation of the energy system, which is still essentially based on fossil fuels. Thus, a mix of different energy sources, intelligent control, the expansion of electricity storage, demand response mechanisms and new business models as well as efficient consumers are necessary to achieve a secure energy supply based on renewable energies, which leads to additional costs and slows down the transformation.
- **Ecological: The European Union's goal is to reduce greenhouse gas emissions by 55 % by 2030 and to achieve climate neutrality by 2050** (European Commission 2022c). In March 2023, the target for the share of renewable energy in energy supply to be achieved by

2030 was significantly increased to 45% (European Commission 3/30/2023). Individual countries, cities and districts are aiming for climate neutrality earlier. In some cases, more far-reaching goals such as PlusEnergy buildings and Positive Energy Districts are being pursued (Brozovsky et al. 2021). In a mission, the EU is pursuing the goal to demonstrate at least 100 climate-neutral cities by 2030 (European Commission 4/28/2022).

From an ecological point of view, the quantity of all greenhouse gas emissions caused by the energy system is the most important indicator, as these are responsible for climate change. However, which polluters of greenhouse gases are included in the target varies; for example, often only the energy needed and greenhouse gases produced by the operation are taken into account, but not the energy consumed and greenhouse gases emitted for the production of the energy system components and the buildings which are consuming the energy. Other indicators could also be considered, for example nature conservation or biodiversity (which can possibly suffer with extensive energy crop cultivation, for example).

Another important challenge of energy planning is the **time dimension**. The main developments influencing the energy system over the period of the energy system's use must be taken into account. Technological developments (e.g., the further cost reduction of renewable energies and the increase in efficiency of technical systems) have a major influence on the optimization of the energy system, as do the expected use and the associated energy consumption (e.g., the assumptions on how strongly energy-saving measures will be implemented). Furthermore, social acceptance and assumptions about the availability of energy imports or land for the use of renewable energies play an important role.

The above points make the complexity of energy planning clear.

3 Procedure for energy planning for GBNs

3.1 General conditions for GBNs

In the following, it is assumed that a GBN achieves climate neutrality by providing the energy used entirely from renewable energy sources (RES). Since the RE potentials within the GBN area are usually not sufficient for this, part of the energy demand must be covered by energy imports into the GBN. If climate-neutral energy imports are allowed by definition, the demand could also be completely covered by imports. However, this would not be in line with the goal of decentralisation and self-sufficiency. Therefore, it is additionally assumed that as much RE as possible is generated in the GBN.

To achieve climate neutrality in the GBN, the following conditions must therefore be met:

- **The energy consumption must be kept low** by efficient buildings and other energy consuming components.
- **The potential of RES in the GBN area must be used as much as possible** and the import of energy into the GBN must be climate-neutral, whereby the use of specific RES potentials from the region is advantageous.
- **The energy system must be designed smartly and efficiently** with storage, sector coupling, intelligent control, and corresponding business models.

The efficient and smart energy system uses sector coupling (electricity - heating - cooling - mobility) where it makes sense to balance the fluctuations of renewable energies (solar and wind energy) through intelligent planning and control. Self-supply of the GBN with as much as possible of the locally generated energy on site is aimed at (e.g., through the use of batteries, heat and cold storage, controlled charging of electric vehicles, energy sharing between neighbours, etc.).

When planning such an energy system, these aspects and goals must be taken into account and the planning method must be suitable for finding an optimal solution for the energy system that can achieve the goals reliably and at the lowest possible cost.

3.2 Recommended steps for the GBN energy planning

It is recommended that energy planning is carried out in the following steps.

1. **Determination of the balancing boundaries and the targets of the GBN**

Determine the specific targets for the GBN (e.g., 100% RES to supply the demand for electricity, heating, cooling and mobility), the target year (e.g., 2035) and the boundaries of the area under consideration, consumers and energy sectors.

2. **Development of a current energy balance**

If it is the redevelopment of an existing neighbourhood, a current energy balance has to be developed as a baseline. For this purpose, energy requirements and energy supply as well as the infrastructure are to be determined and presented in an energy flow diagram. For a new **development, this step should be skipped.**

3. **Forecast of the expected energy demand of the GBN in the target year**

Estimate the energy demand of the buildings belonging to the GBN, taking into account the number of residents and type of building use, as well as the efficiency of the buildings and other energy consumers.

4. **Determination of the potential of renewable energy sources (RES)**

The potentials of RES that can be used in the GBN area are to be determined (required areas and climatic conditions). Similarly, the RES that can be produced in the city and the region and imported into the GBN should be identified.

5. **Evaluation of possible energy technologies that can be used in the GBN**

Identify key parameters such as expected efficiency and costs of RE plants, storage, conversion technology such as heat pumps and expected infrastructure (heat grid, gas grid, etc.) by the target year.

6. **Calculation of the optimal target energy system for the GBN**

Calculation of the most cost-effective solution that achieves the GBN targets using the previously determined input data and assumed framework conditions. After calculating a basic variant, variants of the energy systems are calculated with modified assumptions for the framework conditions (e.g., lower energy demand due to higher efficiency).

7. **Recommendation of a target energy system for the GBN**

Based on the calculation results, the variant that seems most suitable and feasible for the GBN should be recommended.

4 Determination of the balancing boundaries and the targets of the GBN

For an energy system to be planned successfully, the following specifications are necessary:

4.1 Definition of the balancing boundaries of the GBN

Energy systems are usually connected to higher-level, neighbouring or subordinate energy systems (e.g., through the import and export of energy quantities). This often makes the delimitation of the energy system in energy planning difficult. However, a clear definition of the boundaries of the energy system, for which energy planning is being carried out, is essential for successful planning. Care must be taken to ensure that all data used refers to the same reference areas, components, consumers, etc.

- **The following boundaries of the GBNs should be clearly defined at the beginning of the energy planning:** The geographical boundary of the GBN for which the energy system is to be optimised, i.e., the neighbourhood area considered.
- The buildings and other energy consumers belonging to the GBN that are located within the GBN area (this can be more complex if it is not a closed area, e.g., if the GBN represents an energy community in which only individual buildings are involved within a neighbourhood).
- The energy sectors taken into account in the energy balance sheet.
    - Basic sectors: The supply and consumption of electricity, heating and cooling are practically always taken into account, it is to be determined to what extent the following sectors are taken into account:
    - Which types of mobility: local individual passenger transport, public passenger transport, travel transport, delivery transport, long-distance transport, freight transport, etc.
    - Which transport routes are taken into account in the energy balance: Only traffic within the neighbourhood (so called territorial principle) or all traffic of the residents also outside the neighbourhood (so called polluter pays principle), also freight traffic to supply the neighbourhood could be considered. Grey energy:

Energy required for the construction of buildings or their renovation, the energy systems, etc.

4.2 Setting specific targets for the GBN

The concrete objectives of energy planning for the GBN can either be taken from the general definition of the GBN (which has not been done so far) or set by the GBN developers themselves. It is important to clearly define the key indicators and their target values to be achieved through energy planning before starting the planning:

- What is the specific target to be achieved, e.g., zero emissions, residual emissions, or 100% renewable energies, maximum use of renewable energies within the GBN.
- Target year: When is the target to be reached.
- Balancing rules: should the emission and energy targets be achieved on an annual balance or in an hourly balance.

5 Development of a current energy balance

For all GBNs that are not newly built but are created by transforming existing buildings and energy supply structures, a good knowledge of the current energy system is necessary as a starting point for working out the future energy system. The procedure for this is described below.

5.1 Data collection

When collecting data, it must be ensured that all data refer to the defined balance boundaries of the GBN (data of all buildings of the GBN and only the data of the associated buildings). If data are available from sources covering a different area (a larger or smaller one), appropriate conversions must be made. Data are collected for one calendar year, based on the latest year for which all data are available. If the consumption data fluctuate strongly or are influenced by special effects, it may also make sense to use average values over several years. Care must be taken to ensure that all data come from the same year.

First, the **general data of the GBN** area should be collected for the current situation:

- Size and location of the GBN area.
- Number of buildings, their year of construction, floor space and number of storeys.
- Structural status of the buildings (when last renovated, existing thermal insulation, etc.).
- Type of use of the buildings (residential, commercial, school, public building, ...).
- Number of residents or workplaces in the individual buildings.
- Other energy consumers in the GBN.

Then the following **energy data for the GBN** are to be determined:

- Energy consumption of the individual buildings differentiated by sectors (electricity, heating and, if applicable, cooling).
- Energy consumption for mobility depending on the set balance limits.
- As far as possible, the energy data should be differentiated according to consumption sectors (residential, commercial, public buildings, etc.).

- The energy producers in the GBN should be recorded and their annual energy production as well as their energy directly consumed in the GBN and the exported energy.
- Annual values for consumption and production as well as consumption profiles in hourly resolution are needed. If the consumption profiles are not available, appropriate assumptions must be made.

As a rule, the data must be compiled from different sources. In this case, as described above, it must always be checked to which area and which year the individual data refer. If necessary, the data must be corrected to bring them into line with the balancing limits. Some data, e.g., fuel consumption data for transport are mostly not available for the GBN. Then assumptions can be made for e.g., the number of cars, their annual mileage, and the average fuel consumption per km.

Often the load profiles for electricity and heat are not available in hourly resolution. Then, depending on the use of the buildings, standard electricity load profiles from the energy supplier can be used and, depending on the efficiency standard, the heating and cooling load profiles can be modelled with the typical climate data of the location.

5.2 Type of energy data collected

For a sound energy demand analysis, a distinction must be made among primary, secondary, final, and useful energy, as these differ due to conversion and transport losses (see Figure 2).

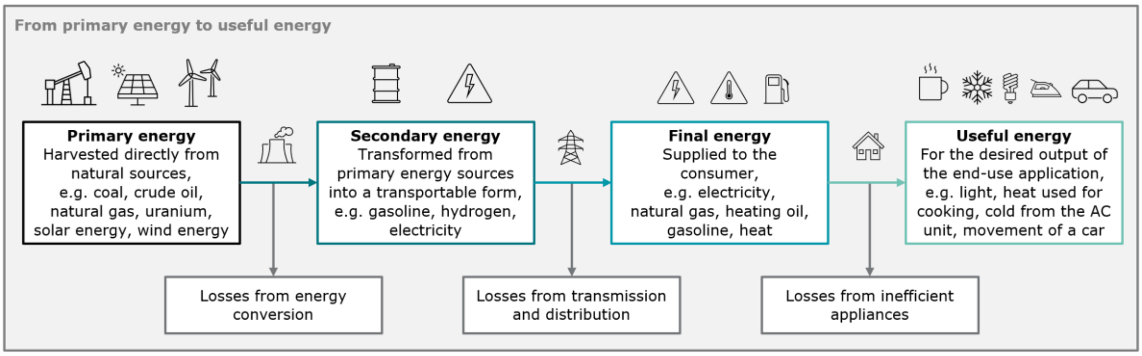

Figure 2: The chain from primary to useful energy with related losses (Source: FRHF).

In the energy balance of the GBN, the final energy is usually recorded, which is the energy that is delivered to the building. The useful energy, e.g., the light from a lamp, the heat for cooking or the kinetic energy for vehicles, is actually the relevant form of energy, but usually the useful energy cannot be measured directly. Primary energy or secondary energy is used, for example, in the form of coal or natural gas in power plants to generate electricity.

The distinction between final and useful energy is relevant because, for example, an electric vehicle only requires about a quarter of the final energy in the form of electricity compared to a combustion engine vehicle powered by petrol. The useful energy (driving the wheels) is the same for both vehicle types, but the final energy (electricity, petrol) is much lower for battery electric vehicles because their efficiency is significantly higher. Another example is the use of LED lighting, which requires only about half the final energy (electricity) compared to fluorescent tubes for the same useful energy (amount of light).

5.3 Energy flow diagram

It is recommended to create an energy flow diagram with the data (so-called Sankey diagram) to make the energy flows visible (see also Figure 5).

6 Forecast of the expected energy demand of the GBN in the target year

In order to actually and efficiently achieve the targeted climate-neutral energy supply of the GBN, the calculation of the energy scenarios must not refer to today's energy demand, but to the energy demand expected in the target year. Assumptions must therefore be made as to how this will develop in the future. The current energy data of existing neighbourhoods serve as an important starting point for the estimation.

6.1 Forecast of the future annual energy demand

Future energy demand in the GBN depends mainly on the following factors:

- The **future efficiency standard** of the buildings in the GBN
  (will they be renovated and to what extent will the thermal insulation be improved).
- The **construction of new buildings** in the GBN (if so, what is their efficiency standard).
- Possible changes in the **use of the buildings** and the number of occupants.
- Possible changes in the **heat supply**
  (e.g., conversion from natural gas-based heating to heat pumps).
- Possible additional **electricity demand** due to new appliances.
- Improvements in **efficiency gains** in other electrical appliances.
- Increase in **cooling demand** and use of air conditioners (due to global warming).

As far as taken into account in the balancing:

- Proportion of electric vehicles, place of charging, change in mobility behaviour.

In the countries of Europe, in contrast to e.g., the Asian countries, only moderate economic and population growth is expected, so that the changes in energy demand are mainly caused by efficiency improvements in the generation, transformation and consumption of energy.

For the estimation of electricity demand, it is particularly important to consider the possible additional consumption due to the electrification of heat supply (with heat pumps and electric heaters) and mobility (with electric vehicles). Appropriate assumptions must be made for this.

The national targets can be used to take into account the increase in efficiency of other electricity consumers.

For existing buildings, the assumptions for efficiency progress in heating demand are decisive. Here, assumptions regarding the expected future efficiency can be made either on the basis of concrete plans of the GBN developers or on the basis of national or European targets (European Commission 2023).

For mobility, the degree of electrification is crucial, as electric vehicles are much more efficient than combustion vehicles. In the long term, a 100% electric vehicle quota can be assumed, especially for local transport. For the GBN energy system, it is important to make assumptions regarding the proportion of electric vehicles that will be charged in the GBN.

6.2 Forecast of the future load profiles

In addition to annual energy demands, assumptions must also be made for load profiles, as much of the future energy generation will be from fluctuating solar and wind energy, and the energy system will be shaped by how well the generation and demand curves match in time. This will determine, among other things, which storage capacities will have to be provided.

It is difficult to predict the electricity load profiles for normal electricity consumption in households, commercial enterprises or public buildings in the future. One possibility is to assume them unchanged from today's demand. However, better assumptions can be made by determining the additional electricity load profile due to a possible electrification of the heat supply. For this purpose, the heating demand of the renovated buildings can be modelled and assumptions for the efficiency of the electric heating equipment (heat pumps) can be made to calculate the corresponding electricity load profile. For the calculation of the additional electricity demand from electric vehicles, estimates of their number, mileage and charging in the GBN are required. In the long term, controlled or bidirectional charging can be assumed, which allows the respective charging power to be adapted to the availability of electricity from renewable energies, as far as the standing times of the electric vehicles allow.

The heating demand, as far as it is not covered by electricity, can be modelled as described assuming the future efficiency standard of the buildings. The same applies to the air conditioning demand.

7 Determination of the potential of renewable energy sources (RES)

For a climate-neutral energy supply of the GBN, it must be determined how large the potential of RES within the GBN is in order to be able to calculate which share of the energy demand can be covered by own resources. The remaining amount of energy has to be imported.

Two different approaches can be chosen for the conditions regarding the import of carbon-neutral energy into the GBN. In the simplest case, energy planners could assume that a sufficient amount of climate-neutral imported energy is available at cheap or acceptable prices at any time when there is a need for energy imports in the neighbourhood. In this case, the design of the local energy system is not influenced by the surrounding energy system, as imported energy is always available when it is needed. A second approach is to prioritise climate-neutral energy from renewable energy sources in the region to import energy when enough cannot be generated locally. In this case, it is first necessary to evaluate what RE resources are available in the region. Their generation profiles must then be taken into account. This can be done, for example, by investing in wind farms in the rural regions around a city or by purchasing biomass. Since rural areas usually have RE surpluses, urban-rural partnerships can be developed to the advantage of both sides and concrete rural RE potentials can be included in the optimisation of the energy system. The second variant is particularly relevant for RE communities that jointly operate RE plants and can exchange the electricity among themselves.

The potentials for solar and wind energy as well as biomass depend on the one hand on the areas available for the installation of solar and wind power plants and for the cultivation of biomass, and on the other hand on climatic data such as solar radiation and wind speed. The rainfall in combination with the topology of the terrain determines the potential for the operation of hydropower plants. The use of geothermal energy depends on the geological conditions, whereby a distinction must be made here between shallow and deep geothermal use.

General methods for determining the individual RE potentials are described below.

7.1 Renewable energies within the neighbourhood

7.1.1 Solar energy

In most cities and neighbourhoods, the solar energy potential on the roofs of buildings (rooftop solar) is the only significant RE potential. Therefore, it is important to determine this in detail. For this purpose, the existing roof areas must be calculated precisely and the roof area shares on which the installation of solar systems is not possible must be deducted (e.g., on dormers, above skylights or where technical devices such as ventilation systems are installed).

For the designation of solar potential, it is important to use the existing roof areas as extensively as possible. For example, almost twice as many photovoltaic modules can be installed on a flat roof with an alternating east-west orientation and 10 to 15 degree inclination of the module rows than with a south orientation of the module rows with about 30 degree inclination and a then necessary row spacing to avoid mutual shading of the module rows (see Figure 3).

Figure 3: South oriented module rows (left) in comparison with alternating east-west-oriented module rows (right).

The facades of the buildings can be considered as further solar potential, although here the yield is lower and the costs are higher. However, there are architecturally very attractive solutions, so that this application will also gain in importance in the future.

The installed photovoltaic power depends on the available installation area. The solar power yield, on the other hand, results from the solar radiation at the respective location and the orientation (east, south, west) and the inclination of the modules.

The usual use of solar energy is the generation of solar electricity by means of photovoltaic systems. However, if there is a significant heat demand in the summer half-year, solar thermal systems for heat generation can also be an interesting solar application.

7.1.2 Geothermal energy

Geothermal energy is the use of the earth's heat. Up to a depth of about 100 metres, there is usually an almost constant temperature of about 10°C. After that, the temperature rises by an average of 3°C for every additional 100 metres, the deeper you go. Geothermal energy can therefore be used in different ways.

Up to a depth of about 400 m, one speaks of near-surface geothermal energy. The temperatures available in this way are not sufficient to provide heat for space heating or for domestic hot water. However, this offers great potential as a primary energy source for heat pumps and for storing heat from summer into the winter half-year.

Heat at higher temperatures is available in layers several 1,000 m deep. Here, water can be extracted at over 80 °C up to several 100 °C with the possibility of also generating electricity. Depending on the geological formation, the temperatures at a certain depth differ, but so do the costs of drilling and the possible extraction rate per borehole.

The easiest way to use near-surface geothermal energy is to drill boreholes to a depth of 100 m, for example, and use heat pumps to provide the desired temperature. If the ground is used for cooling in the summer half-year, it is heated again and thus regenerated for heat extraction in the winter.

If several houses are to be supplied, a so-called cold heat network can be used instead of a central large heat pump, in which only 15 °C heat, for example, is provided in the heat network, which is extracted and decentrally heated in the buildings by heat pumps. This also makes it possible to feed waste heat or solar heat into the decentralized network at relatively low temperatures.

7.1.3 Environmental heat and waste

As a primary energy source for heat pumps, ambient heat can also be extracted from the air or from surface waters. Air-water heat pumps can be installed practically anywhere. However, it should be noted that at temperatures below freezing, the efficiency of heat pumps decreases sharply. In addition, high-performance heat pumps supplying large buildings require a large air flow rate, which can lead to a corresponding noise level. Therefore, the use of shallow geothermal energy is preferable in these cases.

7.1.4 Wind energy

The use of small wind turbines on building roofs in urban areas is discussed again and again. However, experience shows that wind conditions within cities are usually very unfavourable at low heights, as there is a lot of turbulence and the wind speed is usually relatively low. At the same time, the efficiency of small wind turbines is lower than that of large turbines and the costs per unit of power are relatively high. Therefore, the wind potential within cities is usually relatively small and its use relatively expensive. Exceptions to this can be, for example, coastal regions with continuous wind or neighbourhoods that include open areas with high wind speed and with sufficient distance to residential areas to install larger wind turbines.

7.2 Renewable energies outside the neighbourhood

As part of the energy demand usually has to be imported into the GBN, it can also be interesting to examine and use RE potentials in the region around the GBN. This has two advantages. On the one hand, it increases the security of supply and stabilises energy prices. For example, if a wind turbine in the region produces electricity for the GBN, this is usually complementary to the local production of solar power. Since it is uncertain how electricity prices will behave at times of import demand (when typically, all cities have import demand due to lack of solar radiation), wind power generation stabilises electricity costs. On the other hand, wind power expands the possibilities for self-supply and sharing of power within renewable energy communities, which is economically interesting.

Therefore, it is advisable to also investigate the RE potentials in the region. These are primarily the potentials of ground-mounted photovoltaic systems, wind power and biomass.

8 Evaluation of possible energy technologies that can be used in the GBN

An important task is to identify the technologies that could be used in the GBN in the future. This can include technologies that are available today, as well as technologies that are expected to be market-ready and available at the time the GBN will be implemented. Since GBNs are to be realised in the near future, it is not likely that completely new technologies and energy sources will be available that we do not know today. Even if they were, it usually takes several decades before they are ready for the market, which is too long for the current planning of the GBNs. Therefore, it is recommended to plan for technologies that are already widely used today (e.g. photovoltaic systems, heat pumps, lithium-ion batteries), but to take into account the technology improvements expected in the coming years (cost reduction, efficiency increase). It may also be possible to take into account the use of near-market technologies, such as fuel cells, which are so far still being used on a pilot scale but may reach market maturity in the coming years.

- The following is a list of possible technologies that could be considered for use in GBNs in the coming years. Their technical and economic parameters are not listed, however, as they change continuously and may also depend on the location. It is up to the planners to determine these parameters. For electricity generation
    - Photovoltaic systems on roofs, facades, above car parks or on open spaces.
    - Wind turbines in rural areas (outside the GBN and the city)
- For heat generation and supply
    - Solar thermal plants
    - Biomass boilers
    - Geothermal plants (shallow and deep geothermal)
    - Heat pumps
    - Plants for the use of waste heat (from industry, sewers, etc.)
- For cooling
    - Compression refrigeration machines (also reversible)
    - Absorption/adsorption chillers

- For combined electricity and heat generation
    - Biomass combined heat and power plants
    - Photovoltaic thermal collectors
- Plants for the distribution of electricity, heat, and cooling
    - Smart grids
    - Heat grids at different temperature levels (hot and cold grids)
- For storage
    - of electricity: batteries
    - of thermal energy (heat and cold): water tanks for daily storage, above-ground and underground storage for seasonal storage, etc.
- Electromobility charging infrastructure
    - for controlled and bidirectional electric vehicle charging
- Energy management and monitoring
    - Smart energy management system for efficient operation
    - Energy management and billing systems for new business models (e.g., local energy trading)
- Efficiency technologies
    - for reducing electricity, heating, cooling, and mobility consumption (e.g., thermal insulation, efficient appliances, electric vehicles etc.)

For all technologies that come into question due to the local framework conditions, the techno-economic parameters, but at least the expected costs (investment and operating costs) and the efficiencies in the target year are determined, as these are the basis for the modelling.

9 Calculation of the optimal target energy system for the GBN

An optimal climate-neutral energy system for a neighbourhood or a city is characterised by the fact that the local RE potentials are largely utilised, that there is relatively good energy efficiency in the consumption and operation of the energy system, and that the fluctuating RES (especially solar energy) are well integrated into the energy system through sector coupling, storage, and intelligent control. In order to be able to calculate such an optimal energy system, software is needed which, on the one hand, optimises the energy system for all 8760 hours of a year and for all energy sectors considered (electricity, heat at different temperature levels) simultaneously. Such a model was developed at FRHF with the name KomMod (Urban Energy System Modelling Tool). KomMod was used to calculate energy systems of municipalities in different countries and climate zones, thus demonstrating that taking into account both the local renewable energy potential and the energy demand structures depending on the specific location leads to significantly different energy system solutions (Stryi-Hipp et al. 2021).

The energy system components considered (generators, converters, storage, and consumers) and the energy flows between them are shown in the following diagram.

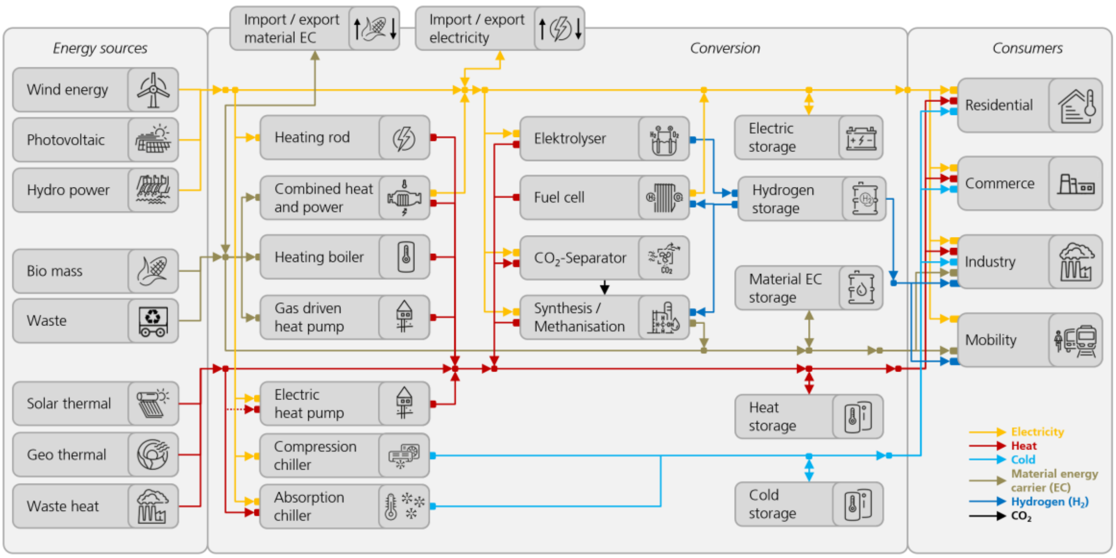

Figure 4: Generic energy flow diagram of a climate-neutral energy system for GBNs with all possible technologies considered in the energy modelling to identify the cost-optimal energy system for the GBN (Source: FRHF).

The KomMod model now uses the previously determined input data to calculate the optimal energy system.

For this purpose, the optimal configuration of the energy system components that need to be installed to use the available renewable energies is determined for the predicted energy demand in the different sectors in the target year. The energy demand for electricity and heat (possibly at different temperature levels) is specified as load curves in hourly resolution for one year. The available RE potentials are also specified, whose generation profiles result under consideration of climate data for the respective location. The orientation and tilt of the modules is used in the case of solar energy to calculate electricity output. The investment and operating costs as well as the efficiencies of all technologies considered in the target year are included.

The results of the model calculation are precise values for:

- Optimal energy system structure (which resources and which technologies).
- Generation and storage capacities
- Effective operating strategy
- Remaining energy import/export
- Investment and operating costs of the energy system

The calculations do not take into account the possible influences of local energy infrastructure on the design of the energy system. It is therefore assumed that the necessary expansion of the electricity grid will take place where necessary and that heating grids will be built where they make sense. Since this energy infrastructure is not included in the energy model, it is also not possible to calculate whether it is more cost-effective to implement a heat grid with central heat supply or only decentralised heat generators, e.g., heat pumps, instead of a heat grid. The reason for this simplification is that the determination of data on costs and technical parameters for local energy infrastructure options is usually time-consuming or not possible. However, the simplification is not a major problem at the municipal level, as the expansion of local energy infrastructure is feasible from a technical or economic point of view and the feasibility of infrastructure solutions can be verified through parallel investigations.

9.1 The KomMod modelling tool

The KomMod tool calculates the optimal configuration of the energy system under the given boundary conditions. It was developed for the calculation of municipal energy systems (from neighbourhoods to entire cities) taking into account the coupling of several energy sectors (electricity, heat, if necessary, at different temperature levels, electricity for mobility) and the priority use of fluctuating RES.

For the calculation, the model is parameterised with the previously collected input data in such a way that it represents the GBN with its expected boundary conditions in the target year. The load profiles for the energy sectors considered are specified for one year in hourly resolution. Furthermore, the climate data for the local site are provided in order to provide a sound representation of the dynamic energy production with renewable energies. KomMod calculates the minimum-cost combination of generation and supply technologies for the specified RE potentials and available technology options. The high dynamics of fluctuating RES and thus of the energy system are taken into account by calculating the overall optimum for all 8760 hours of the year for all coupled sectors. The structure of the energy system that achieves the specified targets (e.g., 100% RES and a minimum quota for self-supply with local RES) in the most cost-effective way is calculated. The total costs are taken into account, which include investment and financing costs, operation and maintenance costs, and fuel costs. However, the infrastructure for energy distribution, e.g., electricity grid or a possible heating or cooling network, and thus their costs are not considered.

Mathematically, the optimisation in KomMod is done by setting up a system of linear equations (LP optimisation problem), which is then solved by an algorithm (based on the SIMPLEX algorithm). In addition to the physical and economic descriptions of the individual technologies, the energy system is described in a system of equations. The central equation is called the objective function and defines the goal of the optimisation. It aims to minimise the levelised annual total costs of the energy system, taking into account the chosen share of RES (usually 100%). The most important physical equations are the energy balances for electricity and for heat. Different temperature levels are represented by separate energy balances in each case. They combine the energy output, restrictions and conditions of each technology with the given demand in each sector. Accordingly, these equations take into account the interdependencies that occur between the technologies in each case and also map the operation of the different technologies (e.g., solar electricity generation is dependent on solar radiation). The energy balances ensure that the energy demand for each energy sector is covered by the energy sources available at the time in every hour of the year. The storage of energy with the associated costs is also taken into account.

9.2 Calculation results of energy system modelling

The results of the optimisation calculations can be displayed in different types of graphics. The energy flow diagram (see example in Figure 5) shows an example of the flows of the different energy sources from the producers to the consumers supplemented by the import and export. The conversion steps and the storage facilities used are also shown. By indicating the installed capacities and the annual energy quantities of the producers, converters, storage facilities and consumers, their respective importance in the energy system becomes clear. Although the energy system is shown without geographical resolution, a distinction is made between the RES within and outside the balance boundaries of the energy system.

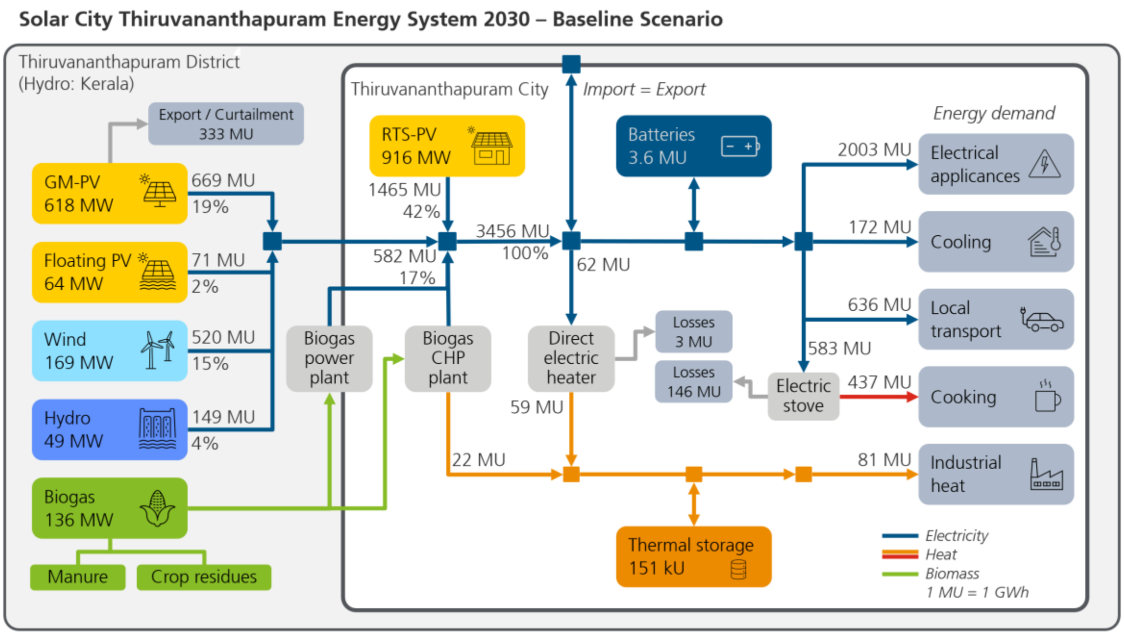

Figure 5: Exemplary energy flow diagram for a climate-neutral energy system based on 100 % RES for the Indian City of Thiruvananthapuram (Source FRHF).

Bar charts (see example Figure 6) show the capacities to be installed and time series graphs (see example Figure 7) show, how the system operates during a time period.

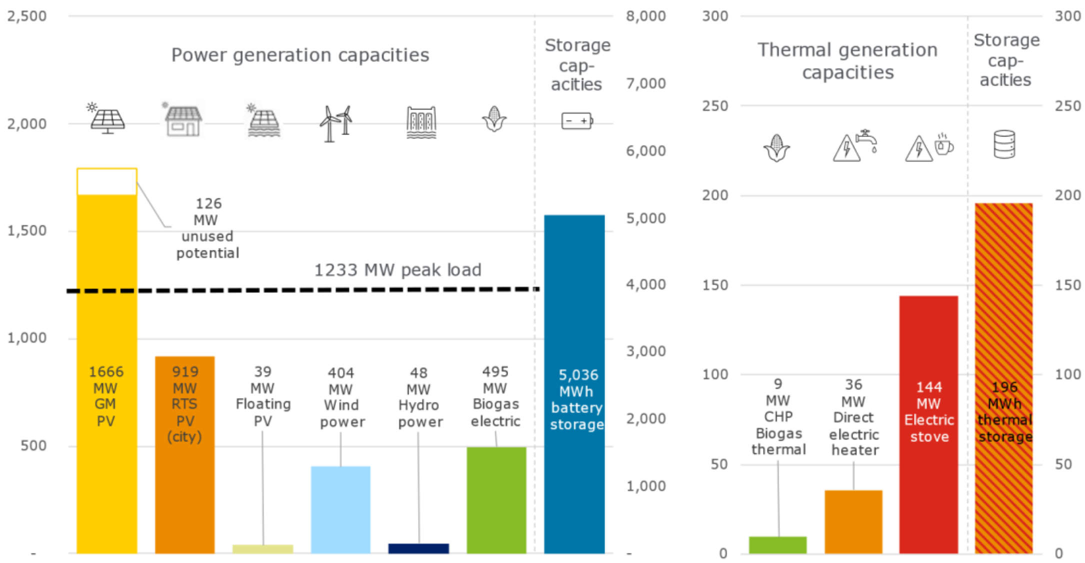

Figure 6: Generation capacities of a climate-neutral energy system of an Indian City for power generation (left) and heat generation (right).

In both graphs, it becomes clear on the one hand that a mix of renewable energies and storage capacities are required to achieve a reliable energy supply, as the temporal dynamics of (solar) power generation and demand do not match. For example, during the day, much more solar power is generated than electricity is consumed, whereas at night, batteries must be used to provide sufficient electricity. The calculations with KomMod now make it possible to determine the cost-optimal mix of generation and storage capacities.

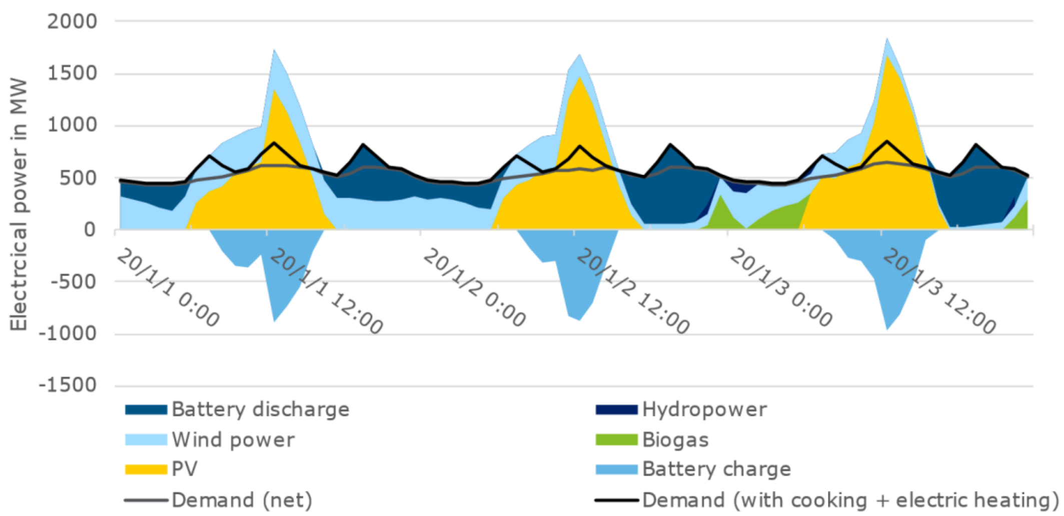

Figure 7: Exemplary diagram of time series, showing how the electricity demand (line) is met by different electricity sources (areas with different colours), for each hour during the 3 days period shown, area below "0" represents charging of the battery.

9.3 Variant analyses of the target energy system

There are several reasons why variant analyses by calculating different scenarios for the future energy system should be conducted. First, the assessments of future energy demands, future costs, etc. are underlying many uncertainties (See also chapter 9.5). In addition, the model is a simplified image of the real energy system. Because of this, variant analyses are inevitable to evaluate the influence of the input data on the modelling results. Second, different scenarios can have a focus on different technologies, like one scenario where wind energy is included and one scenario without wind energy. The comparison between the scenarios can help to understand the cost structure and advantages and disadvantages of using certain technologies. The comparison of a 100 % RE scenario with a least cost scenario and a business-as-usual scenario can show if going 100% renewable is economically viable.

Figure 8 shows exemplarily how the electricity supply mix could change if import prices change. The lower the import price is the more electricity is imported as it is cheaper than producing electricity on site. This is especially true when import is possible at all times as battery capacity can be kept low when electricity is imported instead of producing excess electricity from photovoltaics for later use.

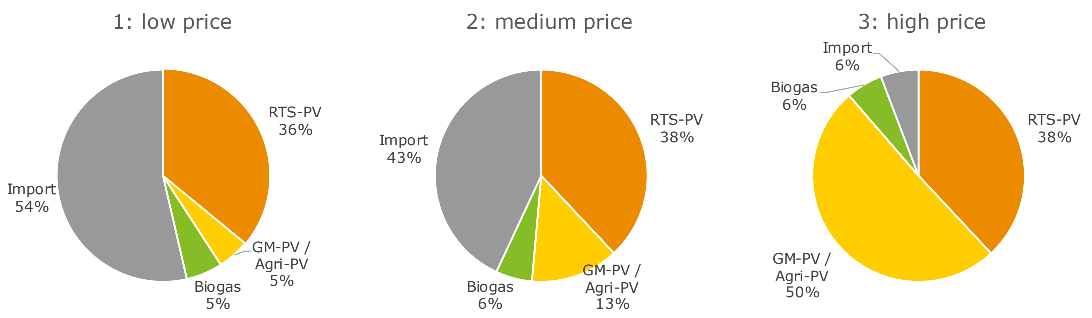

Figure 8: Electricity generation- / import mix at the different import prices from Solar cities India project, Amritsar.

9.4 Selection of the recommended target energy system

From all calculated scenarios (usually about 3 to 5, depending on the case study also more), one scenario is selected whose implementation should be aimed at as the target energy system from the perspective of the study. Decision criteria for the selection are, for example, the total costs, the degree of supply security (e.g., in relation to the degree of self-sufficiency), the robustness of the scenario or the consistency with political guidelines.

A transformation roadmap can be developed for the chosen scenario, showing what needs to be done each year to achieve the energy system in the target year. Figure 9 shows such a transition roadmap for the electricity generation for the city of Avellaneda, Argentina. Today, this city is 100% dependent on imported electricity and no electricity is generated locally. However, the city has high potentials for photovoltaics, wind power and biogas CHP and will be able to fully meet its energy needs in the future, although energy demand is projected to increase.

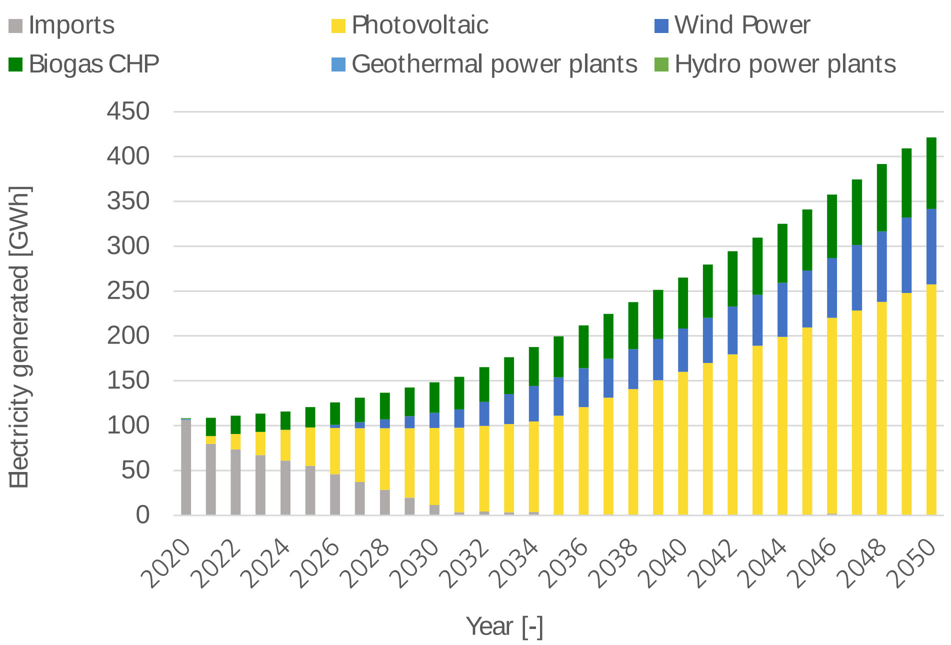

Figure 9: Transition plan for the electricity generation for the city of Avellaneda, Argentina as part of the 100% RE study.

9.5 Uncertainties in the calculation of the energy system

As already elaborated in chapter 9.3, the assessment of future input data comes with uncertainties which make sensitivity analyses necessary. Cost data are by far most difficult to predict, especially fuel prices. For fuels which are traded globally the price is dependent on many factors apart from production costs like production quotas demand for that fuel in different parts of the world and contracts between sellers and buyers. When looking at the price volatility in the past, it gets clear that oil and gas prices can only be roughly estimated. In energy systems that are only dependent on renewable energy carriers no globally traded fuels are used and the two most important energy carriers are usually photovoltaics and wind energy. Here costs are mainly dependent on technological development and solar irradiation/wind speed and therefore less uncertain. But still many different types of input data are used to generate the results and an energy system model is based on simplification of the technical correlations and can never be an exact image of the real world. This is why it often makes sense to not put the emphasis on the absolute results from the scenarios but rather to compare several scenarios and examine the differences. The total costs of the energy system, for example, cannot be compared to real costs of an energy system as not all cost types are incorporated in the model as well as no losses of grids. But the costs of several scenarios can be compared to understand what influence certain input data has on the costs. Figure 10 shows an example from one project where the total system costs of several scenarios are compared, all normalised to the base scenario which has costs of 1. For example, it can be seen how much energy costs change if an alternative scenario on wind power is implemented (no wind) instead of the baseline scenario in which 20 % of the electricity demand is covered by wind power (base scenario). In this example, energy costs would increase by about 7%. A business-as-usual scenario depicts a future energy system following state policies and still using quite a large amount of fossil fuels which leads, under the certain input data, to an energy system being around 1.5 times more expensive than the base scenario using solely renewable energy carriers.

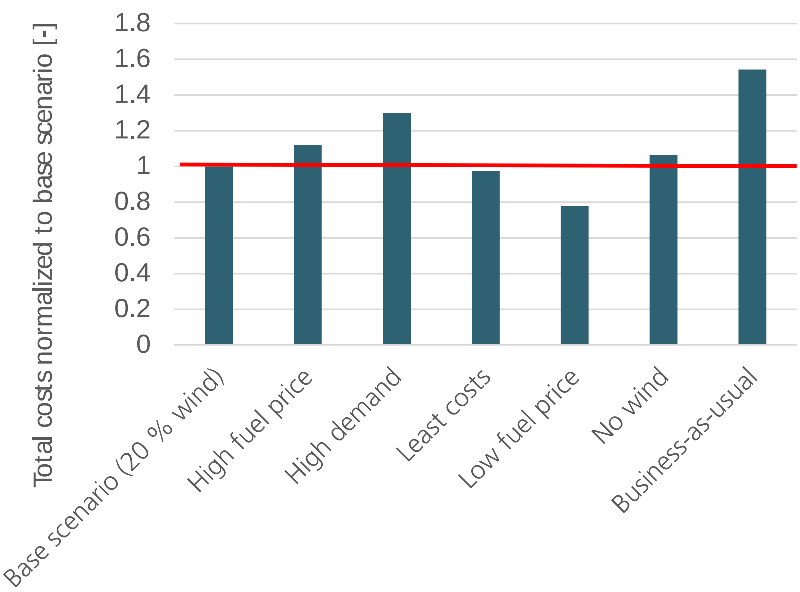

Figure 10: Comparison of the total costs of an energy system in different scenarios for a 100% RE project.

10 Conclusions

Calculating an optimised energy system for GBNs is a major challenge. This is because the energy system must be based on 100% renewable energy including waste heat utilisation due to climate neutrality, should be as efficient as possible and have a high degree of self-sufficiency with renewable energy generated on site. At the same time, the characteristics of future energy systems such as sector coupling, electrification of heat supply and mobility, use of storage and intelligent energy management systems should be taken into account.

Traditional energy planning methods do not meet these demands, which is why new methods and tools have to be used to calculate the energy systems of GBNs.

In this deliverable a new approach of holistic and dynamic energy planning is described. First, the approach is presented on how to collect the input data for the calculation of energy systems and what to pay attention to. Then the energy system modelling tool KomMod is explained, which can calculate optimised energy system solutions with the input data. The results obtained and how they are to be interpreted are also presented.

This describes a modern methodology of energy planning for GBNs, which can be applied to the Living Labs in the PROBONO project in a next step.

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