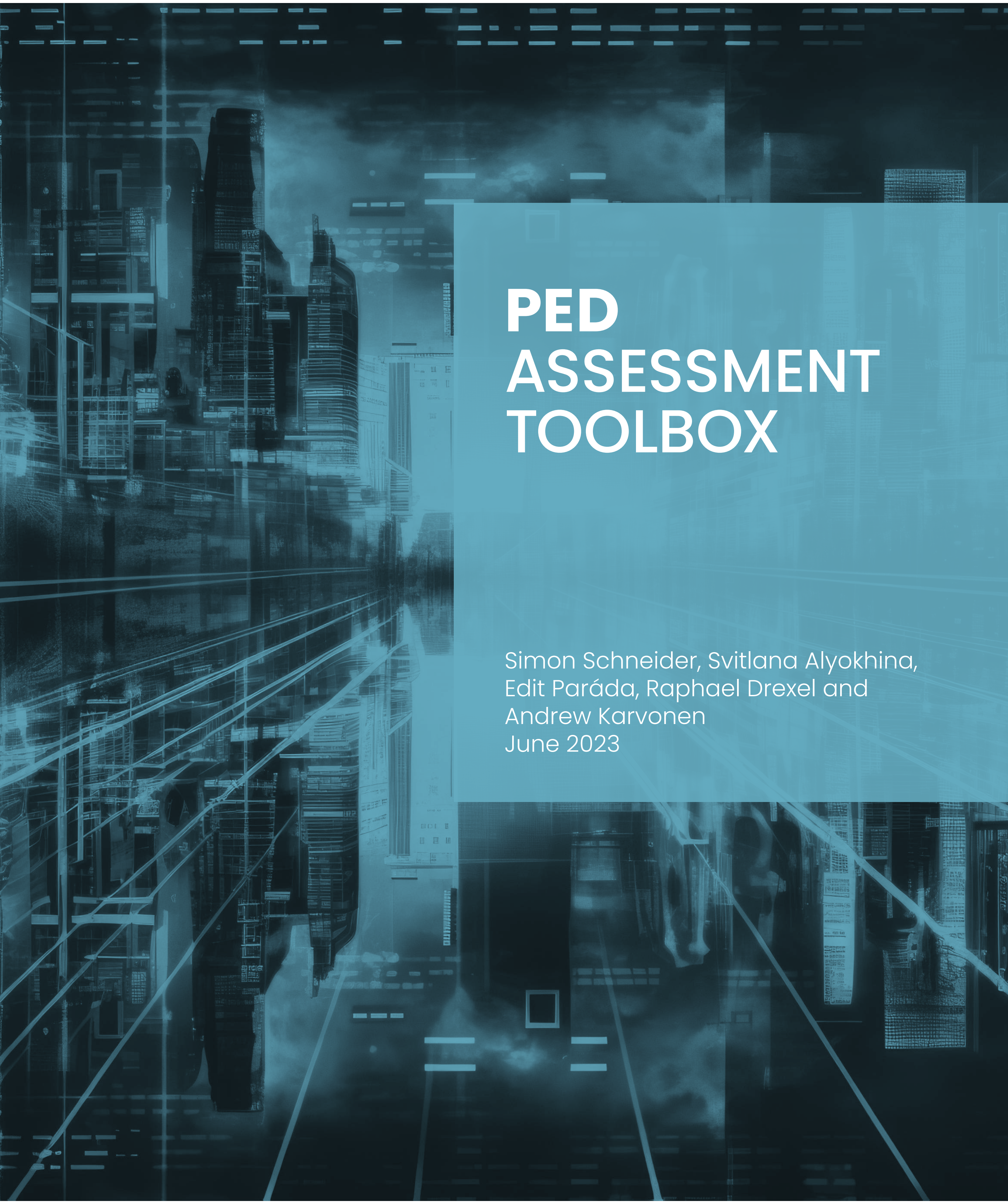
TRANS PED

TRANSFORMING CITIES
THROUGH POSITIVE
ENERGY DISTRICTS



PED ASSESSMENT TOOLBOX

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INTRODUCTION

Positive Energy Districts (PEDs) are pursued through a wide variety of urban contexts and stakeholder constellations. This diversity correlates with the multitude of goals and approaches to assess them. Although there is extensive discussion of the definition and assessment of the PED concept itself – mostly by calculating the energy balance of the PED – there is no uniform or commonly accepted approach to PED assessment. Apart from overall goals and mission statements, how to assess PEDs is non-standardized and specific to each PED.

Most PEDs have diverse ambitions that go beyond a positive energy balance. District goals are multi-dimensional and their assessment typically cannot be limited to the evaluation of a single KPI or metric. Instead, PED stakeholders create their own assessment catalogues based on specific goals and incumbent processes of city planning and district development. PED assessment is not universally defined or even definable but is instead a process informed by local requirements and constraints.

Nevertheless, PEDs are similar to other building and district development and quality assurance processes and many existing methods can be applied to PEDs, such as energy use, energy savings, affordability, security, and so on. Likewise, many PEDs have similar goals and assessment needs. An important gap in replicating PEDs is the lack of dissemination of assessment methods. In many cases, these methods can be adjusted slightly for application to a new PED. This PED Assessment Toolbox provides concrete examples on how existing assessment methods can be applied to PEDs.

AIMS

Another report, Catalogue of PED Assessment Parameters, summarises existing PED assessment methods. This report identifies existing assessment methods from related fields that can be applied to PEDs. It uses the five PEDs of the TRANS-PED project to identify PED assessment needs.

APPROACH AND METHODS

The methods and approaches presented in this report were gathered via the following steps:

1. **Map the assessment objectives of TRANS-PED examples**
2. **Identify the missing assessment parameters**
3. **Present available methods to assess and monitor the missing assessment parameters**

The first two steps were completed through a co-production workshop as part of the TRANS-PED project in September 2022 (Figure 1). In a roundtable format, the project partners engaged in extensive discussions on how to assess PEDs and then addressed the following question:

Which aspect of your PED would you like to assess (in more detail or at all), but do not know exactly how?

The responses were collected and are presented in the following section.

Figure 1: Workshop in September 2022 to brainstorm on assessment possibilities and gaps with the TRANS-PED project partners

PEDS IN TRANS-PED

The PEDs in the TRANS-PED project have diverse characteristics and goals. The following is a quick overview of the more detailed district descriptions available at the project website.[1]

HAMMARBY SJÖSTAD

Hammarby Sjöstad is primarily a residential neighbourhood in Stockholm with ambitious environmental goals. Construction started in 1990 and all infrastructure in the area has now been built. ElectriCITY is a citizen-driven innovation platform for the neighbourhood that was formed in 2012, aimed at making Hammarby Sjöstad climate neutral by 2030. Its "Hammarby Sjöstad 2.0" project serves as a demonstration site and testbed for innovations in energy, transportation, circular economy, digitalisation, and urban agriculture. In the workshop representatives of Hammarby Sjöstad identified three main challenges: 1) legal challenges related to the implementation and monitoring of laws and policy frameworks, 2) the development and establishment of suitable business cases, and 3) the challenge to fully integrate the above into a consistent district system. To this end, the main assessment need for Hammarby Sjöstad is a smart readiness indicator.

ABATTOIR

The Abattoir site is a large industrial slaughterhouse area in the middle of Brussels that is currently being redeveloped. It is a living lab of sustainability where commercial activities, living, working, leisure, and education meet. Fuelled by locally generated renewable energy, rainwater harvesting, and a unique emphasis on human connections and neighbourhood integration, Abattoir has already become a key hub for start-ups in the food industry to address the need for fresh and safe food in urban areas.

One of the assessment needs for Abattoir is a tool to characterise the multiple dimensions of district qualities that combines energy and emissions reductions with other indicators such as social equity and justice.

SONNENDORF

Sonnendorf is a sustainable residential neighbourhood under development in the rural village of Schwoich, home to 2,300 inhabitants in the middle of Austria's alpine region of Tyrol. Once finished, it will consist of 33 buildings with 46 residential units, of which half of the units will be sold to locals at a discount, while the other half will be sold at market price. This unique affordable housing project also paves the way for a modern planning concept in rural areas, focusing on economical land use and a low degree of impervious surfaces.

1 *PEDs - TRANS-PED*. (2023, May 18). TRANS-PED. https://trans-ped.eu/peds/

The main assessment needs for Sonnendorf are 1) to find attractive solutions for the exchange and sharing of locally produced electricity, 2) to find a suitable ownership and management structure for a low temperature local heat network ("anergy network"), and 3) to develop a comprehensive indicator to quantify and visualize energy use and emissions from mobility practices.

GRAZ REININGHAUS

Located on the vast site of a former brewery, Graz Reininghaus is a completely new city district in the making that will ultimately house around 10,000 residents. Its unique location close to the city centre makes it highly attractive for development. The neighbourhood will minimise the need for individual mobility by providing residential areas, offices, commercial space, schools, and a large park in close proximity. It will also have bike lanes, a tram line, and buses to connect residents to the city centre within minutes.

Ironically, one of the key challenges of the district is the high-quality construction that results in high housing prices. This makes it difficult to realize a diverse range of mixed-income residents. Additionally, the utilization of rooftop space for solar energy generation, greening, and recreation creates significant conflicts as well as different neighbourhood perceptions.

The main assessment needs at Graz Reininghaus include 1) a comprehensive indicator to assess the quality and quantity of the available green infrastructure, 2) a universal indicator of efficiency in waste usage, and 3) a household level energy and emissions footprint calculator to incentivize occupants and monitor their activities.

BRUNNSHÖG

Brunnshög is a new sustainable neighbourhood that is currently being developed on the outskirts of Lund, a city of about 100,000 inhabitants in the south of Sweden. With two world-leading research installations (MAX IV and ESS) at its core, the new neighbourhood is where up to 40,000 people will live and work by 2050. While Brunnshög will be a green district with large parks, courtyards, and pedestrian and cycling infrastructure, the project also aims to create a range of sites to support new connections and collaborations among researchers, entrepreneurs, and businesses. Brunnshög has a strong sustainability agenda, including a goal to produce more energy than it needs while promoting cycling, walking, and public transportation over other mobility options.

The main assessment needs at Brunnshög include 1) a calculation of available farmland and impervious surface coverage caused by construction activities, 2) energy and emission benefits of sourcing food locally along with biodiversity and food security impacts, 3) a means to calculate a climate neutral city, including system boundaries and assessment parameters, and 4) a quality of life indicator that accounts for trade-offs with carbon emissions.

1. SMART READINESS INDICATOR

The need to assess the smart readiness of buildings and districts arises from the EU legislation on smart ready buildings and its mandate to establish a national Smart Readiness Indicator (SRI) in all member states. The first operationalization proposal was developed by VITO research institute on behalf of the European Commission. This initial operationalization of the SRI according to a proposed calculation methodology is based on a catalogue of criteria that evaluates the building technology and building services according to their "smart" functionality or "Smart readiness". The SRI assessment is operationalized as a questionnaire-style evaluation tool.

Apart from general information such as location, reference floor space, building usage and building condition or age, the questionnaire focuses on the identification of services and appliances and the level of their "smart" functions: The catalogue lists 27 potential "smart" services in a simplified version and 54 in a detailed version. If a service or group of services does not exist in a given building, the section can be disregarded as it does not contribute to the SRI calculation. The assessment catalogue is divided into nine technical domains, each of which includes several smart services. Table 1 summarises the technical domains and their maximum number of services.

TECHNICAL DOMAIN	NUMBER OF SMART SERVICES
Heating	10
Cooling	10
Domestic Hot Water	5
Ventilation	6
Lighting	2
Dynamic Building Envelope	3
Electricity	7
E-car Charging	3
Surveillance and Control	8

Table 1: Technical domains and the number of smart services in the Smart Readiness Indicator (SRI)

Each smart service is assessed on an ordinal scale from 0 to 4, representing 5 levels of functionality that are qualitatively defined for each smart service. The functionality level of each smart service is further mapped to 7 impact criteria by assigning a score from 0 to 100% in a 5x7 matrix (Figure 2).

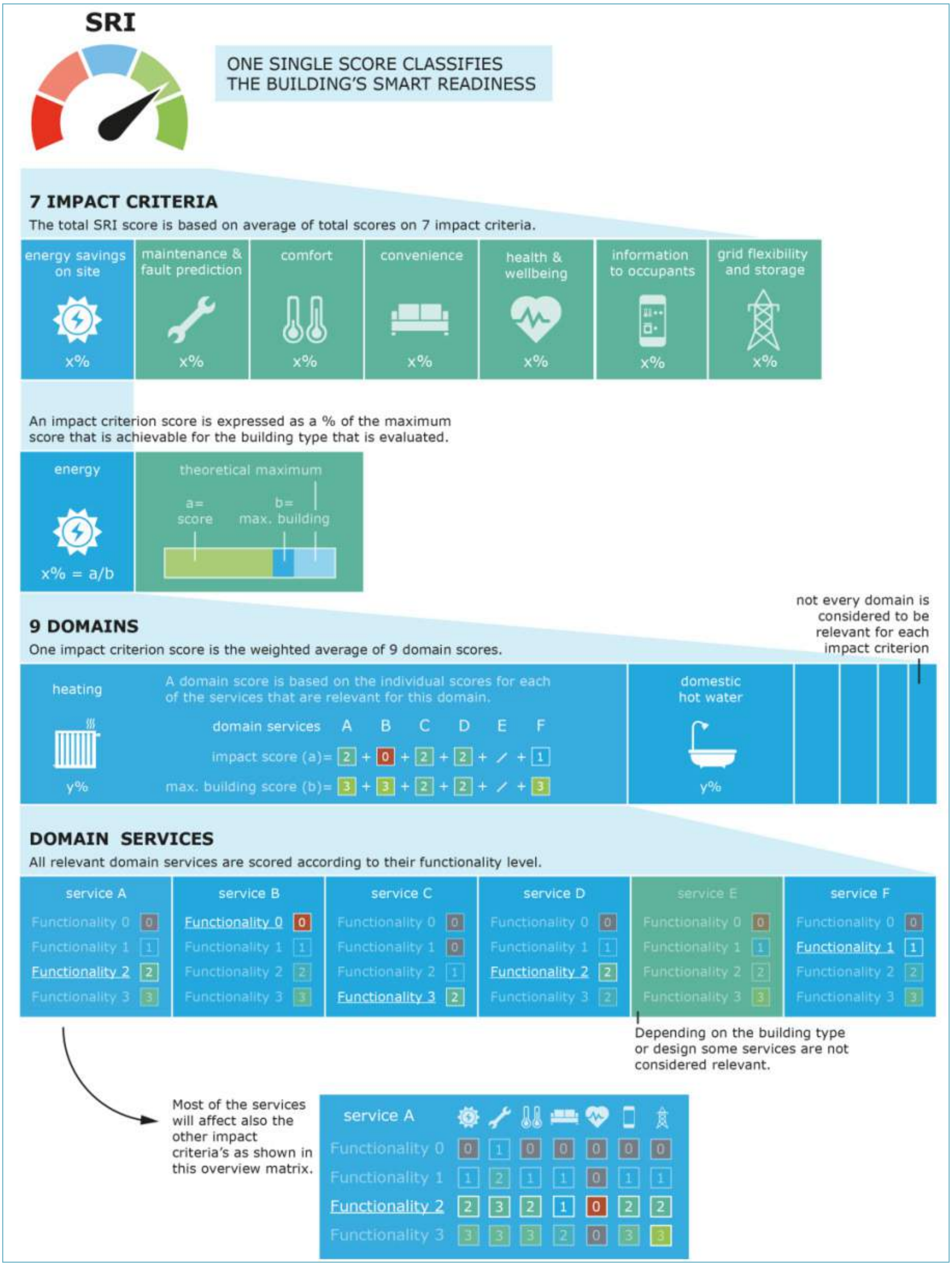

Figure 2: SRI EC/VITO assessment scheme

The final SRI assessment is assembled by weighting the 7 individual impact scores according to a predefined key to a range between 0 and 100% and a corresponding classification (A to E).

This initial proposal had advantages in the seeming simplicity and transparency of the assessment. However, it was also criticised because the weights seemed arbitrary and favoured technological solutions without clear or quantifiable benefits to the user or the environment.

A second example is the Austrian approach, which deviates from the initial proposal. The ***SRI Austria*** Methodology assesses Smart Readiness using three weighted pillars. The first two pillars focus on benchmarking and quantitative analysis while the third pillar is based on the criteria catalogue of the VITO methodology, but is limited to 23 services and evaluated in terms of four impact criteria. Figure 3 shows an overview of the methodology and the weighting of the three pillars.

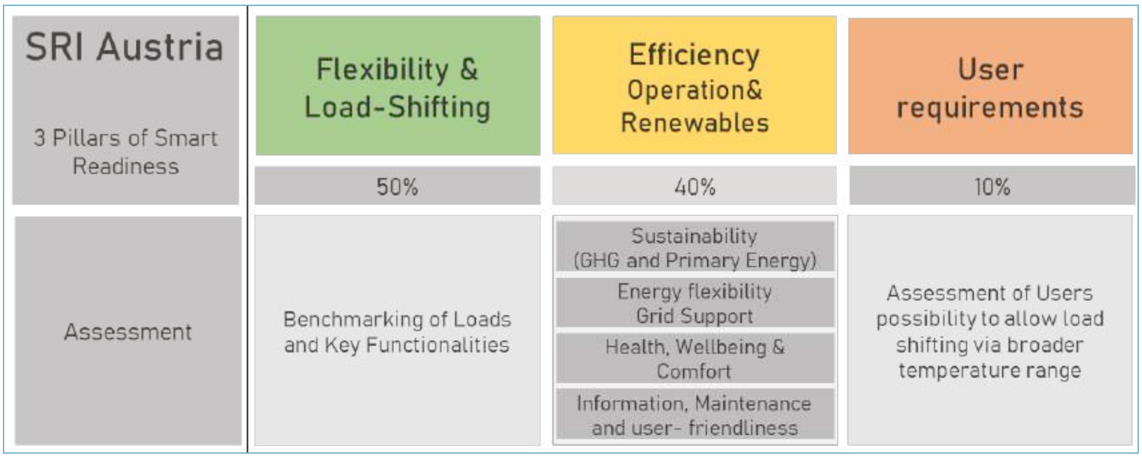

Figure 3: SRI Austria assessment scheme based on a mix of quantitative and qualitative assessments

The first pillar, Flexibility & Load-Shifting, considers thermal and electrical loads, thermal and electrical storage as well as the possible activation of storage masses through low-temperature heating and cooling systems. An alternative or supplementary approach to grid efficiency and the storage capacity of a building or neighbourhood involves the SRI calculation method developed by BOKU[2], which could also be used for this purpose and is currently under consideration for merging with SRI Austria.

The second pillar, Energy Operation & Renewables, is largely based on the methodology developed by the SRI EC. Here, the services and technology domains relevant to Austria were adopted, reduced and reweighted. With the quality catalogue, the assessment aims to ensure a building's ability to be smart. The Austrian implementation focuses on defining impact areas to guide the assessment and weighting of the main assessment categories as follows:

2 *Smart readiness indicator*. (n.d.). Energy. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator_en

- Sustainability of the overall system
  (in terms of GHG emissions and primary energy demand)
- Energy flexibility / grid support
- Health, well-being and comfort
- Information, maintenance, error warning, user-friendliness, and possibilities for intervention

Impact areas such as comfort are also found in the third pillar, User Requirements. For example, by choosing a wide comfort band for room temperature, the building storage mass can be used more effectively for load shifting. Such an approach could be applied to other parameters.

Pillar 1 is weighted at 50 %, Pillar 2 at 40 % and Pillar 3 at 10 %. Further information and updates on the development of the methodology is provided by the European Commission.[3, 4]

An Austrian assessment methodology is currently being developed by a broader consortium of research partners. The report for the original version of SRI Austria is provided on the official website.[5] Both methodologies are in development and practical tests are lacking while usability also needs to be improved. The original VITO method only assesses whether certain services are available and at what level of functionality. The weighting of services and functionalities as well as the assumption and thus the statement that the existence of services implies smart readiness has not been clarified. SRI Austria therefore is pursuing a mixed approach including benchmarking (optimally with simulation) to evaluate smart readiness. However, the methodology is not fully developed or widely tested. For example, the weighting is very simple in some cases and one receives a better rating if any values (planning or simulation) are available. Due to the scepticism towards individual methods, the SRI Demo project is currently attempting to combine the SRI Austria methodology with one developed at BOKU to inform a new adapted proposal for SRI Austria.[6]

3 *Smart readiness indicator.* (n.d.-b). Energy. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator_en
4 *SRI implementation tools.* (n.d.). Energy. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator/sri-implementation-tools_en#for-sri-assessors
5 *SRI Austria - Smart Readiness Indikator: Bewertungsschema und Chancen für intelligente Gebäude.* (2020.). Stadt Der Zukunft. https://nachhaltigwirtschaften.at/de/sdz/projekte/sri-austria.php#publications
6 Knotzer, A., Fechner, J., Zelger, T., & Berger, A. (n.d.). Smart Readiness Indikator: Bewertungsschema und Chancen für intelligente Gebäude (SRI Austria). *Nachhaltigwirtschaften.* https://nachhaltigwirtschaften.at/de/sdz/publikationen/schriftenreihe-2020-08-sri-austria.php

2. INTEGRATED MULTI-DIMENSIONAL PED ASSESSMENT

Klima:aktiv Siedlungen und **Quartiere** is a climate protection initiative of the Federal Ministry for Climate Protection, Environment, Energy, Mobility, Innovation and Technology (BMK).[7] It is an Austrian certification standard that summarizes the essential criteria to plan, construct and operate larger building projects with a focus on climate neutrality and quality of life. It can also be used by municipalities to meet their climate goals by requiring developers to certify their projects and achieve a desired score. District developers can also opt to use the standard to utilize the attached toolkit, develop and formulate their ambitions, and communicate them transparently to potential buyers, tenants and other stakeholders. The certification standard is operated by a federal subsidiary which has the mandate to support and spread it nationally via a strong web-presence with information about the certification standard specifically targeted to relevant stakeholder groups including municipalities, district developers, planners and consultants. The website features links to relevant materials (guides, tools, brochures, and so on), a showcase of best-practices, the certification standard with its criteria and a list of competence partners for matchmaking.

The certification standard can be employed at any stage of district development, but earlier adoption facilitates optimal alignment with district goals and the resulting assessment. The toolkit is specifically designed to accompany and guide the development process with an initial quick check to assess the overall performance potential and direction of the project and subsequent tools and assessments to obtain feedback along the way. Here, the performance in the following six key categories for district development are combined into a single score from 0 to 1000 points. Each category is divided into a number of topics that address all aspects of district development:

A. **Management**: a steering group with clear responsibilities forms the basis for target setting and activities
B. **Communication**: The project potential is identified and leveraged together with all stakeholders using professional communication activities
C. **Urban planning**: attractive public spaces are designed with an appropriate mix of uses
D. **Buildings**: are the core elements of an attractive settlement and are to be implemented in a highly sustainable way
E. **Supply**: Technically, economically and ecologically advantageous heat, electricity and drinking water supplies as well as a well-thought-out waste management are required
F. **Mobility**: Create the basis for environmentally friendly mobility and build new mobility solutions directly at the project site

More information on how each topic is assessed in detail and the results transformed into a comprehensive quantitative points score is presented in Table 2.

7 *klimaaktiv Siedlungen und Quartiere, klimaaktiv.* (n.d.). https://www.klimaaktiv.at/gemeinden/qualitaetssicherung/Siedlungen.html

CATEGORY		ACHIEVABLE POINTS	ASSESSMENT
A	**MANAGEMENT**	**150**	**ASSESSMENT**
A.1	**Establish structures**	25	o whether and how such a steering group is established (10 points) o whether and how the necessary internal and external resources are made available to support the project according to the catalogxue of measures are made available (15 points).
A.2	**Set goals**	45	o whether and how concepts for urban development, buildings, supply and mobility are available (10 points each) o roadmap for their gradual implementation (5 points).
A.3	**Transfer goals and make them binding**	30	o whether and how the following instruments are used to transfer the objectives defined in Section A.2 are used (5 points each): Landowner binding instruments, purchase/lease contracts for land, selection/planning procedures, tenders, purchase or rental contracts for residential units, subsidies
A.4	**Install monitoring**	25	o whether and how the tenant and owner surveys as well as the collection and energy, water consumption, waste quantities and mobility behaviour are planned (5 points each).
A.5	**Conduct controlling**	25	o whether and how the objectives are regularly checked to ensure they are up to date (environmental analysis, 5 points)
			o how changes are responded to (5 points) and whether and how an internal and/or external quality assurance procedure is used (15 points).
B	**COMMUNICATION**	**100**	o **ASSESSMENT**
B.1	**Participation**	55	o whether stakeholder analysis was conducted (5 points) o structure (10 points) and frequency of dialogue with stakeholders (15 points). o whether and how stakeholders were involved in the design of the site (10 points for participation formats and (10 points for participation formats and 15 points for the impact of participation on the design of the site).
B.2	**Sensitisation for Energy and mobility topics**	35	o whether and how concepts for energy, water and waste marketing are available o (15 points) and mobility marketing (20 points) are available.
B.3	**Role model effect**	10	o quality of information (5 points) and the frequency of communication (5 points) are assessed.

CATEGORY		ACHIEVABLE POINTS	ASSESSMENT
C	**URBAN DEVELOPMENT**	**250**	**ASSESSMENT**
C.1	**Building density**	53	o whether and how the project group has dealt with the issue of social and space density, and the planned floor area ratio (53 points).
C.2	**Urban micro climate**	24	o whether and how the microclimate was assessed (8 points) o considerations of relevant aspects of ventilation (8 points) o consideration of greening roofs, facades and open spaces in connection with overheating and evaporation (8 points).
C.3	**Diversity of uses and users**	42	o whether and how the utilization concept is geared to the target groups of the district (13p) o effect of the use concept on the surrounding area (8 points) o mixed uses are planned (8 points) effect on the surrounding area (8 points).
C.4	**Semi-public and public spaces**	57	o whether ground floor uses are planned (13 points) o and if so, their quality (13 points) o space availability in the interior and semi-public exterior spaces (18 points) o possible uses of existing roof areas (13 points).
C.5	**Open space**	46	o number and quality of recreation and open spaces (23 points) o and their use and management concept (23 points).
C.6	**Services for "daily" needs**	28	o distance from relevant facilities to purchase and use everyday goods and services (28 points)
D	**BUILDING**	**150**	**ASSESSMENT**
D.1	**Life cycle costs**	30	o whether and how economic efficiency was analysed for different component and energy system variants, as well as their influence on decisions (30 points).
D.2	**Building certification**	75	o whether, and for how many buildings, building qualities were certified with external labels (75 points).
D.3	**Appropriate density**	45	o planned floor space per person and type of use (25 points) o available space with flexible usage (20 points).
E	**SUPPLY**	**145**	**ASSESSMENT**
E.1	**Degree of self-sufficiency**	35	o share of heat from renewable energy sources on site (15 points). o quality of the heat supply (15 points, including extra points for regional biomass use) o quality of the HVAC planning (5 points).
E.2	**Quality of energy supply**	45	o share of electricity from renewable energy sources on site. (20 points) o quality of the electricity supply (20 points, extra points for certified sustainable green electricity) o quality of the electrical design. (5 points).
E.3	**Efficiency of water use**	35	o expected drinking water consumption per person or alternatively the planned construction and marketing measures to minimise drinking water consumption of the households (15 points), in the outdoor area (10 points) as well as - if available - service buildings (10 points)
E.4	**Waste prevention**	30	o expected amount of waste per person or, alternatively, the planned construction and marketing measures to minimise the amount of waste from mixed (15 points) and non-mixed (15 points) municipal waste.

CATEGORY		ACHIEVABLE POINTS	ASSESSMENT
F	**MOBILITY**	**205**	**ASSESSMENT**
F.1	**Motorised private transport**	26	o number and quality of parking facilities for cars (17 points) o planned type of car park management (7 points) o level of the planned fees/rental charges for the car parking spaces (2 points).
F.2	**Pedestrian and bicycle traffic**	96	o number and quality of parking facilities for bicycles (17 points) o quality of the footpath and cycle path network (27 points) o connectivity to higher-level footpath and cycle path networks, signalized speed reduction and pedestrian zones and accessibility (52 points).
F.3	**Public transport and alternative services**	83	o public transport quality classification of the location (46 points) o Handling and quality of car sharing and other mobility services (37 points).
	TOTAL	**1000**	

Table 2: Assessment categories, achievable points and description

To achieve certification for a project, applicants contract civil engineering firms and sustainability consultancies to complete a self-certification application. This involves completing an Excel spreadsheet that includes a guided questionnaire for most of the subcategories. Two additional Excel spreadsheets are used to conduct a quantitative assessment of the climate compatibility and mobility aspects of the project. The completed self-assessment is audited by certified experts to ensure that the provided information is sufficient.

3. ASSESSMENT OF MOBILITY ENERGY AND EMISSIONS

The assessment of Energy and Emissions from Mobility in PEDs is a hotly debated topic. On one hand, it is desirable to assess at least some of the mobility induced by the district to incentivise concrete reduction measures and assign responsibility. On the other hand, the inclusion of the energy demand for mobility in the energy balance makes it much more difficult to achieve a positive balance – especially in dense urban areas where this can be infeasible. Additionally, there is a lack of calculation methods to estimate the energy demand of and emissions from mobility, especially a priori and without extensive monitoring campaigns, which would be necessary for the objective and uniform assessment of mobility energy and emissions.

The following is a generalization of the mobility assessment approach used in the Austrian definition and operationalization approach *Zukunftsquartier*, that focuses on a transparent, normative assessment as part of the energy balance assessment (see Figure 4).[8] This method requires multiple parameters that can be specified differently.

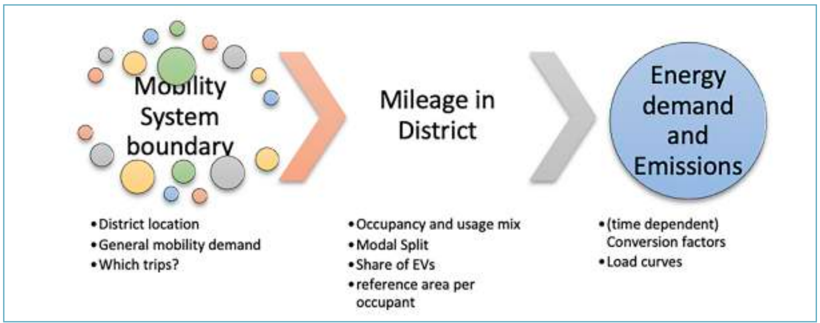

Figure 4: Main steps determining PED mobility energy and emission demand

Results are obtained through the following step. First, the system boundary for the mobility services considered in the demand calculation is determined. It is useful to break this down into the following mobility categories and sub-categories:

- **Everyday Mobility**
  - Private mobility
    - Motorized
      - Fossil
      - Electric
      - Other
    - Other
      - Pedestrian
      - Bicycles
  - Public transport
    - Bus, Trams, Subways, Rail, and so on
  - Other services
    - Sharing Facilities (EV, Bike Share, Cargo Bike Share, and so on)
- **Other**
  - Holiday travel and other sporadic occasions (e.g., flights and cruises)

8 Schneider, S., Zelger, T., Sengl, D., & Baptista, J. (2023). A Quantitative Positive Energy District Definition with Contextual Targets. *Buildings*, *13*(5), 1210. https://doi.org/10.3390/buildings13051210

In the proposed assessment, only the *individual everyday mobility* is included. This is because the assessment follows the principle of subsidiarity, according to which the smallest possible unit in a system should have the greatest possible autonomy in dealing with tasks. For a neighbourhood, this is possible due to its location and corresponding options of individual forms of mobility. It therefore makes sense to locate the coverage and creation of options for individual everyday mobility as the district's responsibility. Public transport on the other hand, is a superordinate mode of transport that primarily serves to connect neighbourhoods with one another and with other means of transport. The accessibility of a neighbourhood or settlement can strongly depend on the development of public transport. Conversely, project developers rarely influence the design of public transport. Moreover, more energy-intensive infrastructure is necessary for public transport, which also serves the general public beyond the neighbourhood. It therefore seems sensible to budget for public transport in terms of energy and emissions at a higher level than that of the neighbourhood. These budgets could in turn be allocated to the neighbourhoods, but this again raises the non-trivial question of the allocation method, which is even more complex for public transport than for individual everyday mobility, because the occupancy density and the allocation of trips to benefits is less clear. The time of consideration also plays a major role here, as neighbourhood projects and their development with public transport do not always take place at the same time and according to the original plan.

Next, the selection of mobility services to be included involves the following considerations:
- Data availability to derive mileages for the relevant services in the district
- Aim and scope of the energy and emission balancing and subsequent requirements of inclusion and omission of services
- Achievability of balancing targets

Further considerations are whether to cover source or destination travel or both. Theoretically, it can be argued that mileage originates from both the location of source and destination, and is thus the shared responsibility of both. Not considering multiway travel, a location typically is as much a destination of a trip as it is the source, which is why in the presented approach it is arbitrarily defined that only destination travel is the responsibility of the PED, shared equally with the virtual source of the traffic. The presented approach on the mobility environment and system boundary considerations is summarised in Table 2.

Consideration	What?	Why?
Which mobility services are considered?	Only **individual motorized** mobility	Because the PED can take measures to decrease associated emissions and should be incentivized to do so.
Inclusion of Source and/or Destination travel	Only **destination** travel	Because of data availability and all travel being the equal responsibility of source and destination, statistically approximating half, or only considering the destination

Table 2: Main considerations for mobility assessment

This results in a quantitative estimate of mileage travelled within the defined system boundaries, which is subject to the previously mentioned considerations. Depending on available data sources, the mileage can be further detailed based on usage mix and location of the district.

For example, an Austrian mobility dataset that features average mileages per person, mode of transport and destination (categorized as residential, commercial, education, retail and other).[9] Figure 5 shows public transport accessibility as "Mobility regions" where grey indicates three levels of metropolitan access (best), red indicates good access in urban environments, yellow indicates moderate access in semi-urban/semi-rural areas and green indicates low access in rural and less accessible areas. The darker the colour in each category, the higher the public transport access. Each region includes a modal split and mileage figures per person and annum, differentiated into four main destinations: Residential, Office & Commercial, Education and Other. Based on these studies, an analyst can identify the share of individually motorized modes to be assessed.[10]

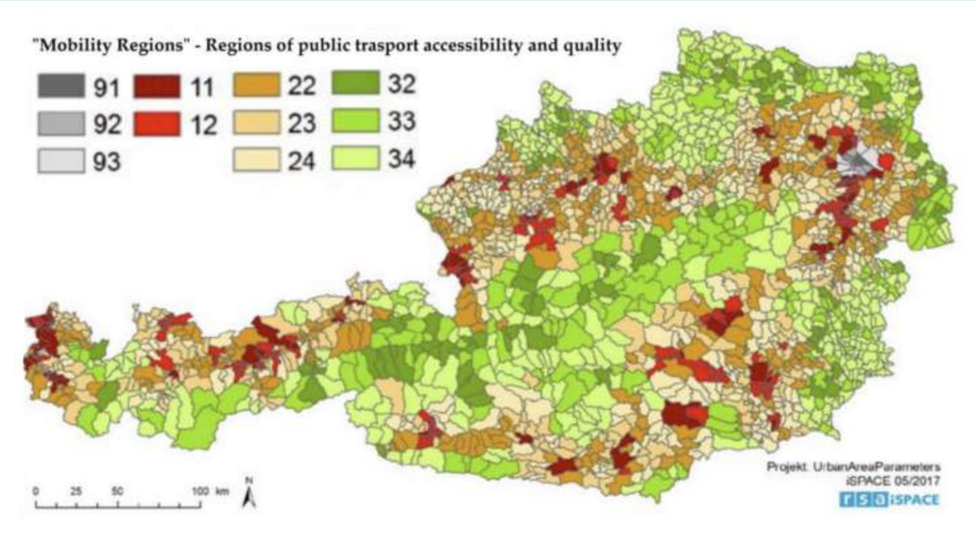

Figure 5: An Austrian example of mobility regions with corresponding mileage per modal split[11]

The next question is how to convert personal mileages and modal splits of inhabitants and users to an aggregated mobility energy demand of a district.

A seemingly straightforward way might be to use statistical or project specific occupancy rates to estimate statistically averaged mileages and modal splits for the district. This works reasonably well for residential uses but for other uses. This is because actual occupancies can vary significantly from planning data, especially for non-residential uses. This has to do with occupancy rates reflecting worst case heat and cooling load considerations, at times grossly over- or under-estimated the actual space used. Instead, only actual, of if unavailable, statistical average occupancy rates should be used for mobility demand estimation. These Occupancy rates might only be available for residential uses. For other uses, they can be estimated by aggregating all areas of that usage type in the country and dividing by the number of inhabitants, as presented by the statistical mileage profile. This distributes the mobility demand burden statistically equally across all usages and assumes, for example, that all shops are equally crowded or all office buildings equally empty.

The general approach is illustrated in Figure 6. It is only useful if the purpose of the mobility assessment is to standardize and compare project ambitions. If the goal of the assessment is to monitor mobility reduction, other approaches such as surveys and sensors would be more suitable.

9 Herry Consult. Project report Urban Area Parameter Mobility; Reports from Energy and Environmental Research; Austrian Research Promotion Agency: Vienna, Austria, 2017.
10 Mobilitydata Austria. (n.d.). https://mobilitydata.gv.at/en
11 Schneider, S., Zelger, T., Sengl, D., & Baptista, J. (2023). A Quantitative Positive Energy District Definition with Contextual Targets. Buildings, 13(5), 1210. https://doi.org/10.3390/buildings13051210

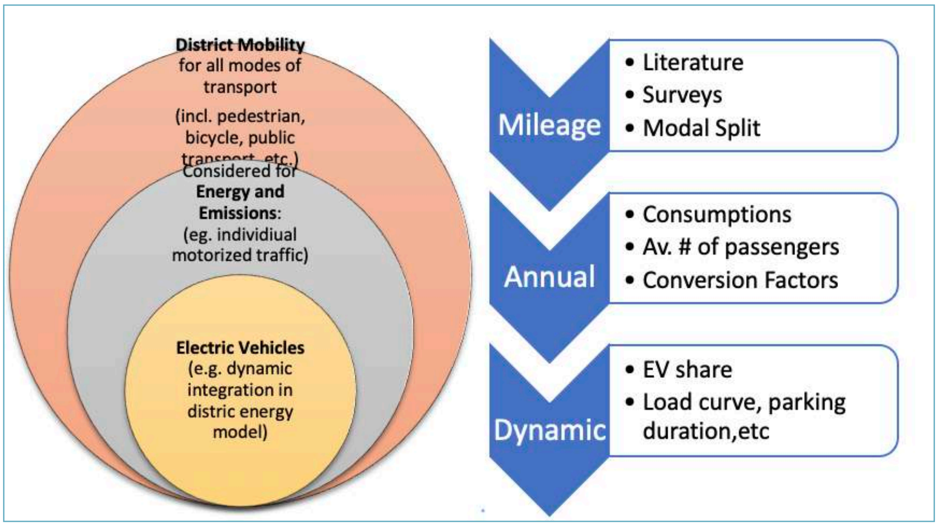

Figure 6: Example schematic operationalization of mobility energy and emission assessment

The mobility demand is calculated on the basis of the total floor space distribution according to the uses (residential, office, school-like and trade & other). An average floor space per inhabitant and occupant is determined and scaled with the average mileage per inhabitant to arrive at a statistical average mileage per floor space. This can then be combined with models and assumptions on measures to reduce mileage, fossil fuel consumption, increased share of electric vehicles and ultimately converted to energy and emission demands per space use as shown in Figure 7.[12]

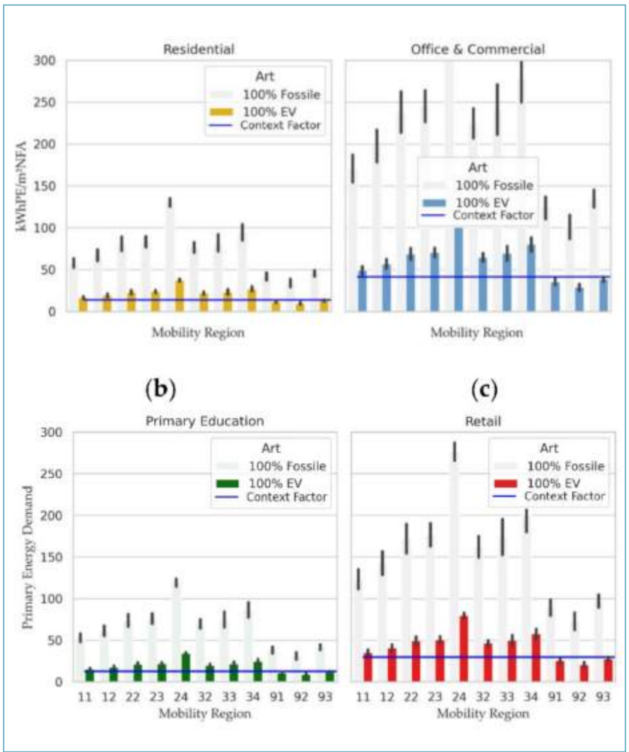

Figure 7: Example result range of mobility energy demand quantifications for different space uses (colours) and mobility regions (bars)

12 Schneider, S., Zelger, T., Sengl, D., & Baptista, J. (2023). A Quantitative Positive Energy District Definition with Contextual Targets. Buildings, 13(5), 1210. https://doi.org/10.3390/buildings13051210

The advantage of this statistical and normative approach is that it also allows for the allocation of a mobility energy and emission budget from the surrounding future decarbonized energy system to be considered and used to cover these demands (at least partially). This can be done with a predefined context factor as shown in Figure 8.[13]

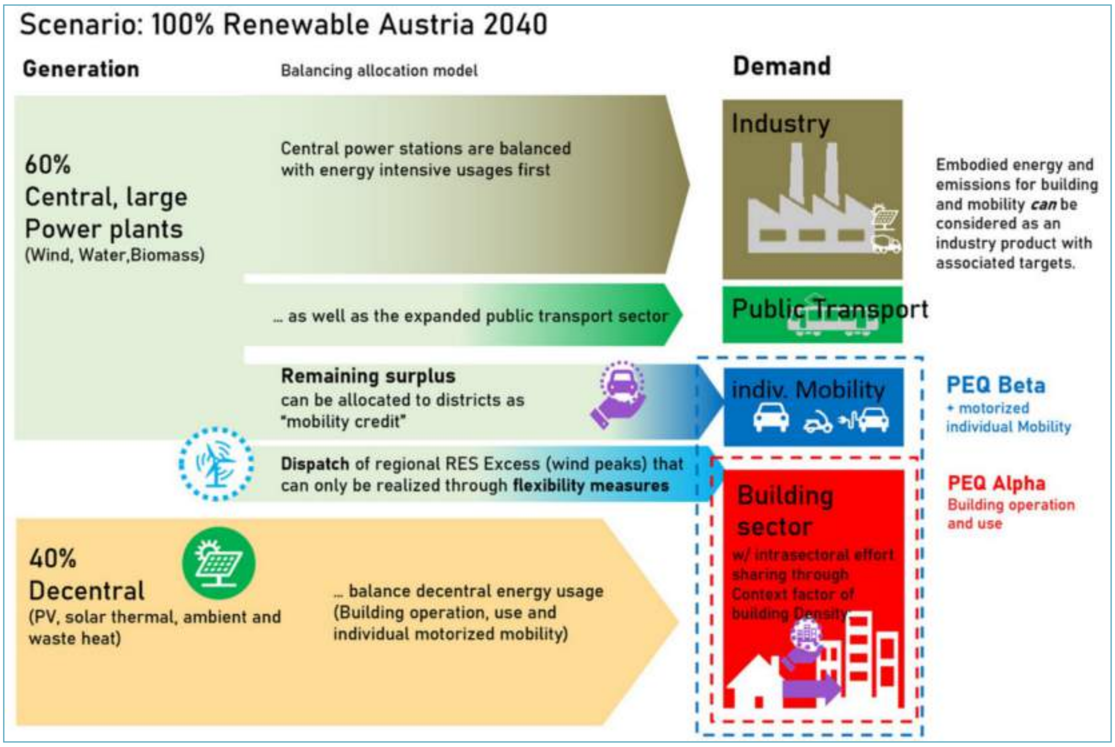

Figure 8: Example of a district mobility budget from national decarbonization scenarios

This enables the inclusion of motorized individual mobility in the PED energy balance through an allocation mechanism as depicted in the centre of national supply and demand matching. It requires both supply and demand targets to match a normative energy system scenario. This approach is exemplified for two PEDs in the Cities4PEDs project.[14]

13 Schneider, S., Zelger, T., Sengl, D., & Baptista, J. (2023). A Quantitative Positive Energy District Definition with Contextual Targets. Buildings, 13(5), 1210. https://doi.org/10.3390/buildings13051210

14 Schneider, S. (n.d.). Definition of Positive Energy Districts. *Energy Cities*. Retrieved September 25, 2023, from https://energy-cities.eu/wp-content/uploads/2023/07/Cities4PEDs-WP2-Definition-.pdf

4. GREEN INFRASTRUCTURE

Green infrastructure plays a significant role in PEDs to reduce energy demand.[15] The absence of green infrastructure leads to lower quality of life and environmental pollution, and serves as an obstacle to PED implementation. At the same time, the analysis and evaluation of green infrastructure is challenging and their representation in the literature is limited.

Some studies focus on urban distribution and emphasise the use of satellite data and remote sensing image processing.[16] To evaluate the status of green distribution, one study developed an algorithm with a supervised classification method using MLC (Maximum Likelihood Classifier) to characterise land surface entities. The index of Green Area/Capita was used to evaluate environmental quality and urban space. However, the authors focused on green space evaluation methods rather than the role of green areas in PEDs.

In another study, the urban fabric was analysed based on the building-oriented method by considering four main parameters: Green Space Index (GI), Proximity to Green, Building Density and Building Height.[17] These building characteristics were combined in a land use model to inform more effective land suitability analysis and urban planning. This approach could also be used in different stages of PED development and implementation.

A similar approach was proposed in a study that developed the Building's Proximity to Green Spaces Index (BPGI) to quantify a building's neighbouring green spaces.[18] However, the index is only applicable to individual buildings while groups of buildings and neighbourhoods must be studied separately.

The quantitative use of the green space index has also been studied with respect to environmental pollution.[19] Here, the authors used five types of green space indexes in relation to city development areas to assess their potential for further development.

The dynamic of the green space index was also studied through the development of an Urban Green Space Index (UGSI) and Per Capita Green Space (PCGS).[20] The researchers developed formulas to inform performance metrics such as average precision and accuracy that could be applied to PEDs.

Some authors have identified strong correlations between the green space index and other PED KPIs. For example, green spaces have been proven to have a positive effect on decreasing local traffic noise pollution.[21] The presence of trees, plants, and other forms of vegetation can act as natural sound barriers and help to mitigate noise pollution and create a more peaceful and tranquil living environment. This is illustrated in Figure 9 where the correlation value indicates the strength of the relationship between noise levels and the presence of greenery.

15 Privitera, R., & La Rosa, D. (2018). Reducing Seismic Vulnerability and Energy Demand of Cities through Green Infrastructure. *Sustainability*, *10*(8), 2591. https://doi.org/10.3390/su10082591
16 Han, T. T. N., Hoa, P. K., Khoa, H. B., & Van, T. T. (2018). Understanding Satellite Image-Based Green Space Distribution for Setting up Solutions on Effective Urban Environment Management. *IECG 2018. https://doi.org/10.3390/iecg_2018-05342*
17 Liu, Y., Meng, Q., Zhang, J., Zhang, L., Jancso, T., & Vatseva, R. (2016). An effective Building Neighborhood Green Index model for measuring urban green space. *International Journal of Digital Earth*, *9*(4), 387-409.
18 Li, X., Meng, Q., Li, W., Zhang, C., Jancsó, T., & Mavromatis, S. (2014). An explorative study on the proximity of buildings to green spaces in urban areas using remotely sensed imagery. *Annals of GIS*, *20*(3), 193–203. https://doi.org/10.1080/19475683.2014.945482
19 Zangiabadi, A., & Rakhshaninasab, H. R. (2009). The statistical-spatial analysis of urban green space development indices (case study: Isfahan urban zones). *Journal of Environmental Studies*, 105-116.
20 Aryal, J., Sitaula, C., & Aryal, S. (2022). NDVI threshold-based urban green space mapping from sentinel-2a at the Local Governmental Area (LGA) level of Victoria, Australia. *Land*, *11*(3), 351.
21 Margaritis, E., & Kang, J. (2017). Relationship between green space-related morphology and noise pollution. *Ecological Indicators*, *72*, 921-933.

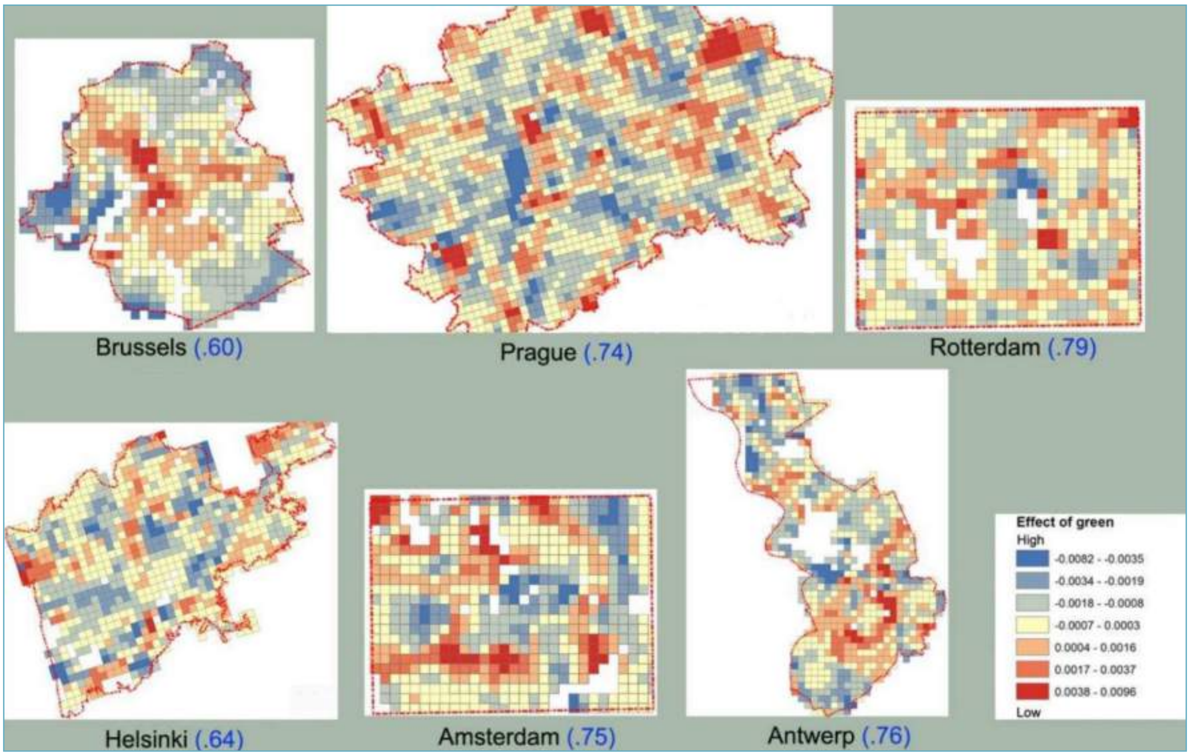

Figure 9: The effect of green spaces on noise based on a Geographically Weighted Regression model

In PEDs, technical aspects of green infrastructure should be considered in conjunction with economic, social, legal and other issues. Several studies highlight the economic, social and environmental benefits of green infrastructure and provide methods for their evaluation.[22,23] A more nuanced understanding of the value of green infrastructure can help communities decide where, when and to what extent green infrastructure practices should become part of future planning, development and redevelopment of PEDs.

Green infrastructure and building energy efficiency are important parts of the economic aspects of PED implementation.[24] Green infrastructure can produce a double positive effect on cities by triggering retrofitting and reducing the energy demand to cool the existing urban fabric.

22 Wolf, K. L. (2003). Ergonomics of the city: Green infrastructure and social benefits. In *Engineering Green: Proceedings of the 11th National Urban Forest Conference. Washington DC: American Forests* (Vol. 115).
23 Gallet, D. (2011). The value of green infrastructure: A guide to recognizing its economic, environmental and social benefits. In *WEFTEC 2011* (pp. 924-928). Water Environment Federation.
24 Privitera, R., & La Rosa, D. (2018b). Reducing Seismic Vulnerability and Energy Demand of Cities through Green Infrastructure. *Sustainability*, *10*(8), 2591. https://doi.org/10.3390/su10082591

Green and Open Space Factor in Austria

The Green and Open Space Factor (GOSF) can be used to establish a target to achieve a sufficient degree of greening in a district. The GOSF is a tool that can be used to plan, implement, and manage green infrastructure. According to the formulation of a target for the GOSF of a property[25], the following objectives should be achieved:
– **Improvement of microclimate and air quality**
– **Preservation of soil function and water balance performance**
– **Increase in the availability of habitat for animals and plants**

The factor is calculated as the ratio of the natural and climate-effective surfaces of a property compared to the total plot area. The different types of green and open surfaces are weighted according to their ecological efficiency. The natural and climate-effective area is the sum of the different types of areas multiplied by their respective weighting factors (see Figure 10).

For instance, roof greening is assigned a GOSF of 0.7, indicating its relatively high contribution to green and open spaces.[26] Facade greening, on the other hand, has a GOSF of 0.6, reflecting its slightly lower ecological efficiency. Surfaces with some permeability are assigned a GOSF of 0.3, while impermeable surfaces have a GOSF of 0.0 since they do not contribute to green and open spaces. Vegetated areas with a direct ground connection, such as parks and gardens, have a GOSF of 1.0, representing their maximum ecological efficiency and contribution to green and open spaces.[27]

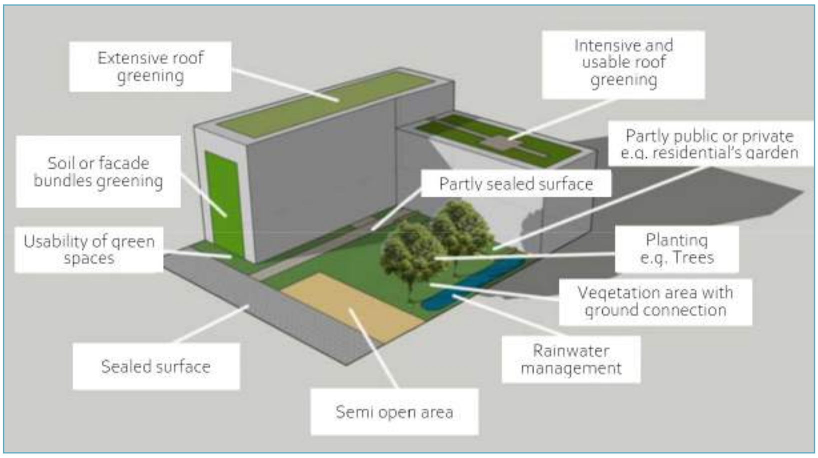

Figure 10: Greening area types[28]

Facade and roof greening measures can be used to combat building overheating in summer months. Additionally, building greening can reduce air pollution, noise and dust pollution, as well as CO_2 emissions.

25 Becker, C. W. (1990). „Der Biotopflächenfaktor als Ökologischer Kennwert-Grundlagen zur Ermittlung und Zielgrößenbestimmung ".
26 Reinwald, F. (2017). „Klimafaktor Boden - Bedeutung von Bodenverbrauch und Bodenversiegelung für die Klimawandelanpassung".
27 Ring, Z., Damyanovic, D., & Reinwald, F. (2021). Green and open space factor Vienna: A steering and evaluation tool for urban green infrastructure. *Urban Forestry & Urban Greening*, *62*, 127131.
28 Reinwald, F. (2017). „Klimafaktor Boden - Bedeutung von Bodenverbrauch und Bodenversiegelung für die Klimawandelanpassung".

Roof greening also results in lower surface temperatures compared to bitumen and gravel roofs, with a difference of approximately 25-33 °C.[29] On a sunny summer day, it can reduce heat transmission by 30-60% compared to a gravel roof. When the substrate is dry, noise can be reduced by 8 dB, and by 18 dB when the substrate is moist. Green roofs provide 2-10%[30] more insulation in winter and 3-10% less heat loss compared to gravel roofs.

Facade greening can lower the surface temperature of facades by 8-19 °C and reduce transmission heat loss by up to 25%. Wall-bound facade greening can reduce noise by 4-9 dB and achieve up to 7 °C higher air temperature in the ventilated cavity during winter. It can also reflect 40-80% of solar radiation. Using facade greening can result in primary energy savings of 49% compared to a building without sun protection.

The cooling effect of rooftop and façade greenery can also yield synergies with PV solar collectors, which have higher operating efficiency in colder temperatures.

Green roofs evaporate approximately 45% of annual precipitation, increase humidity by 20-40%, and reduce air temperature by a maximum of 1.5 °C at the roof level. They can sequester approximately 0.80.9 kg/m² of CO_2 and about 10 g/m² per year of fine dust. Extensive green roofs can retain an average of 75-90% of rainfall, and retention of precipitation in intensive substrates ranges from 60 to 99%.

With facade greening, a higher relative humidity of about 20-40% in summer and 2-8% in winter can be achieved. It sequesters 2.3 kg/m² of CO_2 and produces 1.7 kg/m² of O_2 per year. Facade greening can reduce air temperature by 5 °C on a hot day.

29 Enzi, V., Formanek, S., & Peritsch, M. (2020). *Green Market Report Austria Kompakt - Bauwerksbegrünung in Österreich - Zahlen, Daten, Märkte*. BMK. https://nachhaltigwirtschaften.at/resources/sdz_pdf/schriftenreihe-2020-27-green-market-report-kompakt.pdf
30 Mann, G., & Mollenhauer, F. (2019). *GRÜNSTATTGRAU-Fachinformation „Positive Wirkungen von Gebäudebegrünungen (Dach-, Fassaden- und Innenraumbegrünung)"*. BuGG. https://gruenstattgrau.at/wp-content/uploads/2021/07/gsg_fachinformation_positive-wirkungen-von-gebaeudebegruenung.pdf

5. WASTE UTILIZATION

Waste utilization can be assessed both in terms of material and energy flows. Energy utilization can be assessed as the share of energy and exergy used from collected waste. This can be connected to municipal and national waste utilization strategies that define minimum relative thresholds of energy and material content used.

The Waste Management Hierarchy is a framework that prioritizes different waste management strategies based on their environmental impact.[31] The hierarchy typically consists of the following stages, listed in order of importance:

1. **Prevention:** The most important stage is waste prevention. This involves reducing waste generation at the source through product design, packaging reduction, and promoting sustainable consumption practices. By preventing waste from being created in the first place, environmental impacts are minimized.
2. **Recycling:** The next stage is recycling, which involves the collection and processing of waste materials to create new products. Recycling helps conserve resources, reduce energy consumption, and minimizes the need for raw material extraction. It plays a crucial role in closing the loop and promoting a circular economy.
3. **Recovery:** The recovery stage focuses on the recovery of energy or other valuable resources from waste. This includes waste-to-energy incineration and anaerobic digestion where waste is converted into electricity, heat, and biofuels. Recovery helps reduce reliance on fossil fuels and can contribute to renewable energy generation.
4. **Disposal:** Disposal is the last resort in the waste management hierarchy. It involves the safe and environmentally sound disposal of waste that cannot be prevented, recycled, or recovered. Disposal methods may include landfilling and other forms of controlled waste disposal to ensure minimal negative impacts on the environment and human health.

By following the waste management hierarchy, the focus is placed on preventing waste generation, maximizing recycling efforts, and utilizing waste as a resource whenever possible, while minimizing the need for disposal. This approach aims to reduce environmental pollution, conserve resources, and promote sustainability in waste management practices. The waste hierarchy is illustrated in Figure 11.

31 Zhang, C., Hu, M., Di Maio, F., Sprecher, B., Yang, X., & Tukker, A. (2022). An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. *Science of the Total Environment*, *803*, 149892.

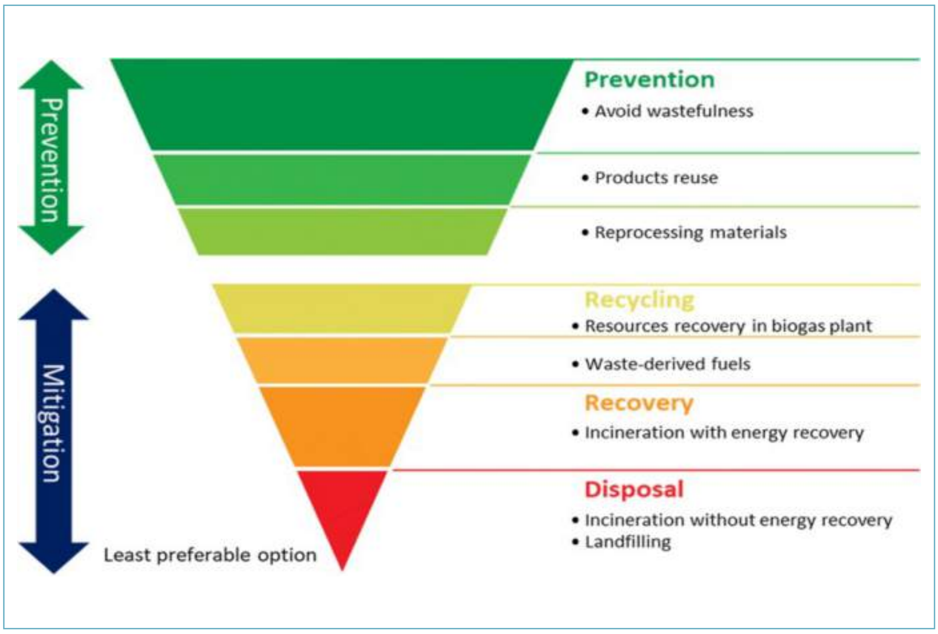

Figure 11: Overview of waste management hierarchy[32]

One of the most popular and essential aspect of waste management is the co-generation of energy and high-value products and their disposal. Despite some criticisms, this approach produces renewable energy and has zero or negative carbon cycle implications as well as lower environmental impacts.[33,34,35] Naturally, a waste-to-energy approach is very attractive for PEDs. Figure 12 shows the possible waste-to-energy pathways with their respective feedstocks and desired products.

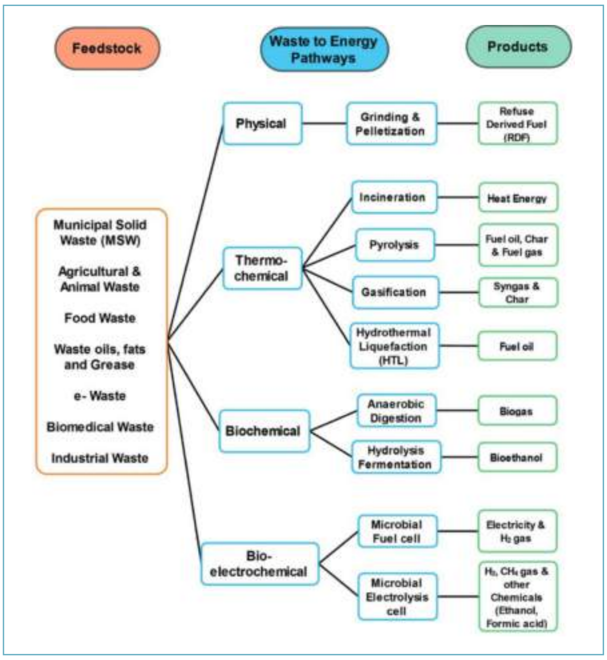

Figure 12: Different waste-to-energy pathways to transform feedstocks into desired products

32 Tsui, T., & Wong, J. W. C. (2019). A critical review: emerging bioeconomy and waste-to-energy technologies for sustainable municipal solid waste management. *Waste Disposal & Sustainable Energy*, *1*(3), 151–167. https://doi.org/10.1007/s42768-019-00013-z
33 Seltenrich, N. (2016). Emerging Waste-to-Energy Technologies: solid waste solution or dead end? *Environmental Health Perspectives*, *124*(6). https://doi.org/10.1289/ehp.124-a106
34 Mayer, F., Bhandari, R., & Gäth, S. (2019). Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies. *Science of the Total Environment*, *672*, 708-721.
35 Mishra, A., Siddiqi, H., & Meikap, B. C. (2022). Elucidating sustainable waste management approaches along with waste-to-energy pathways: A critical review. *Energy from Waste*, 83-96.

TRANS PED

PED implementation requires renewable energy sources and waste utilization to support it. Waste utilization strategies require estimates of future energy utilization patterns and related environmental impacts, potential solutions to current environmental problems and renewable energy technologies and the identification of waste-to-energy routes.[36]

For example, waste-to-energy systems can be considered in conjunction with hydrogen production.[37] Such systems can achieve energy and exergy efficiencies of 32.7% and 36.6% respectively.

However, hydrogen production from waste is not a new idea and has been studied by many authors. An early study of waste-to-hydrogen involved hydrogen production using a combination of photovoltaic electricity and energy from a waste plant.[38] The study also considered mobility issues (e.g. converting automobiles to the hydrogen as a fuel) which is important for PED implementation.[39]

Contemporary studies tend to focus on hydrogen production using eco-friendly biological technologies to reduce GHG emissions. [40,41] There is a close correlation between organic waste utilization and the resulting energy balance of the waste-to-energy system.[42] The capacity of biogas production and its energy efficiency can be estimated through an analysis of the waste management strategy. A few R&D projects have developed hydrogen production techniques that correlate with PED goals. [43,44] In Finnish study, researchers estimated the potential for waste heat recovery in a district with buildings constructed between the 1960s and 1980s.[45] Waste-to-energy strategies can also address waste heat utilization. The integration of waste heat recovery systems can result in energy consumption reductions as well as improvements to economic and environmental performance.[46]

The term "waste" is included in KPIs for PEDs. For example, "symbiotic waste heat legal framework compatibility" measures the suitability of legal frameworks to integrate symbiotic waste heat solutions. This criterion is qualitative and is addressed in the legal KPIs of PEDs.[47] Another KPI addresses the "Heat Recovery Ratio" or the percentage of the total thermal energy output of the system compared to the thermal energy recovered through a waste heat recovery technology.[48] There are also KPIs such as "Municipal Solid Waste" and "Recycling Rate of Solid Waste" that assess the environmental aspects of waste utilization. The former KPI measures how much waste a city is producing and the level of service a city is providing for its collection while the latter KPI is the amount of the solid waste recycled divided by the amount of solid waste produced.[49]

Social issues must also be considered with respect to waste utilization strategies.[50] Specifically, "Not In My Back Yard" (NIMBY) effects need to be considered when planning the development of the required infrastructure for waste utilization.[51]

36 Kothari, R., Tyagi, V. V., & Pathak, A. (2010). Waste-to-energy: A way from renewable energy sources to sustainable development. *Renewable and Sustainable Energy Reviews*, *14*(9), 3164-3170.
37 Gungor, B., & Dincer, I. (2022). A renewable energy based waste-to-energy system with hydrogen options. *International Journal of Hydrogen Energy*, *47*(45), 19526-19537.
38 H Power cogen system for Swedish 'green' project. (2002). *Fuel Cells Bulletin*, *2002*(5), 6–7. https://doi.org/10.1016/s1464-2859(02)80522-3
39 Euro–Canadian alliance to buy fuel cell buses, London's H2 from waste. (2006). *Fuel Cells Bulletin*, *2006*(12), 5–6. https://doi.org/10.1016/s1464-2859(06)71264-0
40 Akroum-Amrouche, D., Akroum, H., & Lounici, H. (2019). Green hydrogen production by *Rhodobacter sphaeroides*. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *45*(1), 2862–2880. https://doi.org/10.1080/15567036.2019.1666190
41 Badawi, E. Y., Elkharsa, R. A., & Abdelfattah, E. A. (2023). Value proposition of bio-hydrogen production from different biomass sources. *Energy Nexus*, *10*, 100194. https://doi.org/10.1016/j.nexus.2023.100194
42 Comparetti, A., Febo, P., Greco, C., Navickas, K., Nekrosius, A., Orlando, S., & Venslauskas, K. (2014). Assessment of Organic Waste Management Methods through Energy Balance. *American Journal of Applied Sciences*, *11*(9), 1631–1644. https://doi.org/10.3844/ajassp.2014.1631.1644
43 *Waste2H2 - Waste to hydrogen*. (n.d.). Retrieved September 25, 2023, from https://waste2h2.eu/
44 Rwe. (n.d.). FUREC. https://www.rwe.com/en/research-and-development/hydrogen-projects/furec/
45 Korpela, T., Kuosa, M., Sarvelainen, H., Tuliniemi, E., Kiviranta, P., Tallinen, K., & Koponen, H. K. (2022). Waste heat recovery potential in residential apartment buildings in Finland's Kymenlaakso region by using mechanical exhaust air ventilation and heat pumps. *International Journal of Thermofluids*, *13*, 100127.
46 Ni, T., Si, J., Lu, F., Zhu, Y., & Pan, M. (2022). Performance analysis and optimization of cascade waste heat recovery system based on transcritical CO_2 cycle for waste heat recovery in waste-to-energy plant. *Journal of Cleaner Production*, *331*, 129949.
47 Angelakoglou, K., Nikolopoulos, N., Giourka, P., Svensson, I., Tsarchopoulos, P., Tryferidis, A., & Tzovaras, D. (2019). A methodological framework for the selection of key performance indicators to assess smart city solutions. *Smart Cities*, *2*(2), 269–306. https://doi.org/10.3390/smartcities2020018
48 *Grow Smarter :: Publications*. (n.d.). https://grow-smarter.eu/inform/publications/
49 International Organization for Standardization. ISO 37120: Sustainable Cities and Communities-Indicators for City Services and Quality of Life; International Organization for Standardization: Geneva, Switzerland, 2018
50 Renn, O. (2003). Social assessment of waste energy utilization scenarios. *Energy*, *28*(13), 1345-1357.
51 Achillas, C., Vlachokostas, C., Moussiopoulos, N., Banias, G., Kafetzopoulos, G., & Karagiannidis, A. (2011). Social acceptance for the development of a waste-to-energy plant in an urban area. *Resources, Conservation and Recycling*, *55*(9-10), 857-863.

6. ENERGY & EMISSION FOOTPRINTS AT THE HOUSEHOLD LEVEL

The PED concept is closely related to energy demand and CO_2 emissions. Usually, these issues are considered at the level of the district, neighbourhood or city.[52] However, it is important to consider the household level as a structural unit which comprises the energy and emission profiles of the city as a whole. Possible data sources include statistical projections (exemplified by the Urban Area Parameters Project) and (self-)reporting tools. Meanwhile, calculating household level footprints can be challenging due to transitive issues i.e. (what if the size of the household changes?) as well as validity (how accurate is self-reporting?).

One study developed a carbon footprint inventory for household consumption in 177 regions across 27 EU countries (see Figure 13).[53] The authors highlighted the spatial heterogeneity of embodied greenhouse gas emissions within multiregional countries and identifies significant differences in regional contributions. The study provided a breakdown of regional emissions by consumption categories and evaluated the driving forces of carbon footprints, including income, household size, urban-rural typology, education level, expenditure patterns, temperature, resource availability, and carbon intensity of the electricity mix. The findings emphasized the importance of incorporating consumption-based accounting into local decision-making. However, a lack of cross-national region-level studies has limited the ability to draw broader policy conclusions.

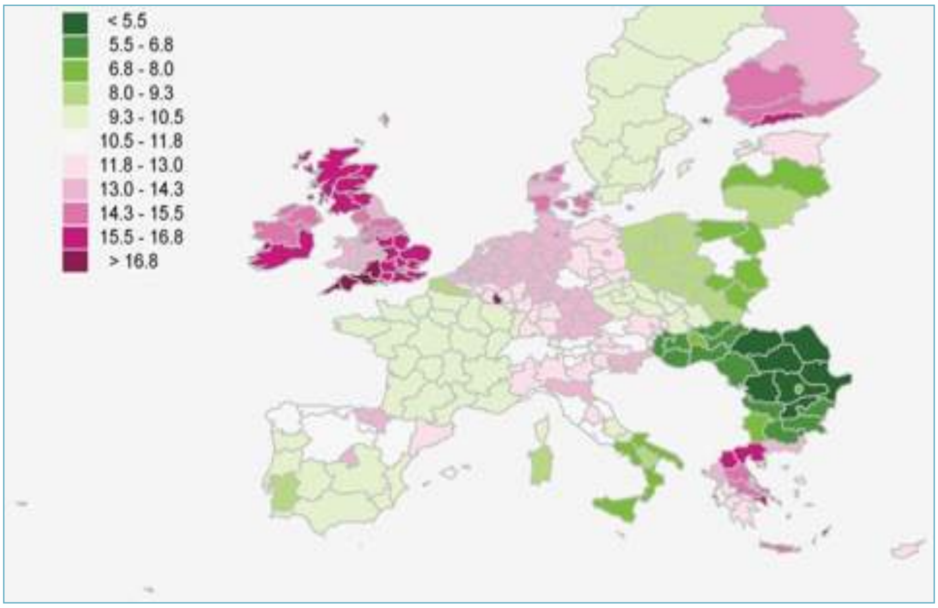

Figure 13: Average household carbon footprint (Ivanova et al. 2017)

52 Van De Graaf, T. (2017). Is OPEC dead? Oil exporters, the Paris agreement and the transition to a post-carbon world. *Energy Research & Social Science*, *23*, 182–188. https://doi.org/10.1016/j.erss.2016.10.005
53 Ivanova, D., Vita, G., Steen-Olsen, K., Stadler, K., Melo, P. C., Wood, R., & Hertwich, E. G. (2017). Mapping the carbon footprint of EU regions. *Environmental Research Letters*, *12*(5), 054013.

Many studies are devoted to household carbon emissions. A common problem involves the generalisation of household profiles for assessment. Some studies have used reduced coefficients, such as CO_2-equivalents per square meter and CO_2-equivalents per capita to address this problem.[54,55] These studies show that CO_2 emission reductions can be achieved by increasing population densities and adopting low-carbon energy technologies.

Another issue is the assessment of a large number of households. In a study by Goldstein et al. (2020), the data of about 93 million individual homes were evaluated. A study by Lee et al. (2021) developed statistical projections of household carbon footprints using a consumption-based accounting framework to solve the problem of big data handling through scaling and urban-rural weighting.[56] Energy and carbon footprints usually correlate with various types of consumption, which can be studied with a multi-regional input-output model to evaluate consumption per unit of expenditure.[57] Different methods of simplification and approximation can be used to estimate household footprints.

In contrast to the aforementioned methods, the “self-assessment” approach can be used to calculate household footprints.[58] Self-assessed environmental sustainability evaluations reflect individual attitudes toward the environment more precisely than footprint calculations. However, this approach can have high levels of uncertainty. There are many online self-assessment calculators and tools but they are mostly used for educational purposes.[59]

Self-assessment approaches can be classified as social scientific methods.[60] To be used effectively for PED development and implementation, these methods should be combined with household footprint calculations.

FOODPRINT (THE FOOTPRINT OF THE FOOD)

The term “foodprint” refers to the overall impact of food production on the environment. The foodprint includes energy consumption, greenhouse gas emissions, water usage, soil erosion, land use, and other environmental impacts. Studies evaluating foodprints use different methods and indicators to quantify environmental impacts throughout the entire life cycle of food, including cultivation, processing, transportation, storage, retail, and disposal.

54 Goldstein, B., Gounaridis, D., & Newell, J. P. (2020). The carbon footprint of household energy use in the United States. *Proceedings of the National Academy of Sciences*, *117*(32), 19122-19130.
55 Long, Y., Dong, L., Yoshida, Y., & Li, Z. (2018). Evaluation of energy-related household carbon footprints in metropolitan areas of Japan. *Ecological Modelling*, *377*, 16-25.
56 Lee, J., Taherzadeh, O., & Kanemoto, K. (2021). The scale and drivers of carbon footprints in households, cities and regions across India. *Global Environmental Change*, *66*, 102205.
57 Vargas-Solar, G., Khalil, M., Espinosa-Oviedo, J. A., & Zechinelli-Martini, J. L. (2022). Greenhome: a household energy consumption and CO_2 footprint metering environment. ACM Transactions on Internet Technology (TOIT), 22(3), 1-31.
58 Bleys, B., Defloor, B., Van Ootegem, L., &Verhofstadt, E. (2018). The environmental impact of individual behavior: self-assessment versus the ecological footprint. Environment and Behavior, 50(2), 187-212
59 Franz, J., & Papyrakis, E. (2011). Online calculators of ecological footprint: do they promote or dissuade sustainable behaviour?. *Sustainable Development*, *19*(6), 391-401.
60 Cosmi, C., Dvarionienė, J., Marques, I., Di Leo, S., Gecevičius, G., Gurauskienė, I., Mendes, G., & Selada, C. (2015). A holistic approach to sustainable energy development at regional level: The RENERGY self-assessment methodology. *Renewable and Sustainable Energy Reviews*, *49*, 693-707

In one study, the carbon and land footprint of 26 certified food products, including geographical indications and organic products, were calculated using a Life Cycle Assessment approach.[61] The study found that the carbon footprint per ton of product did not significantly differ between certified foods and their conventional counterparts, except for organic vegetables which had a 16% lower carbon footprint. However, certified foods that met various food safety standards had a 26% lower climate impact per hectare and a 24% higher land footprint compared to uncertified foods. This pattern was influenced by factors such as reduced use of mineral fertilizers and variations in yield. Overall, the assessment supports the promotion of certified food as compatible with climate change mitigation efforts.

Another study examined the impact of local foods on health, food security, and social capital in communities.[62] The authors found that engagement with the local food industry improved community health through increased awareness and access to healthy food. The authors also found that local foods can address food insecurity, particularly in low-income areas. However, the study identified several limitations and critiques of local food movements. These include a lack of rigorous analytical support and inconsistent definitions of "local." There are concerns about the limited growth potential and sustainability of alternative food networks, as well as the need for fair and equitable production practices. The study emphasized the importance of evidence-based research and cautious decision-making in promoting local food systems. Decision-makers should consider the potential risks and benefits of local food investments compared to other investment opportunities. It is essential to ensure that local food initiatives bring tangible benefits to communities and prioritize social equity.

The study included a spatial analysis of the local food index (Figure 14) to identify patterns of local food activity across counties in the United States. The analysis revealed higher levels of local food activity in certain regions, including parts of Minnesota, the Great Lakes area, New England, and the Pacific coast. On the other hand, there was relatively less activity in areas such as the Mountain West, eastern Texas, and parts of Florida.

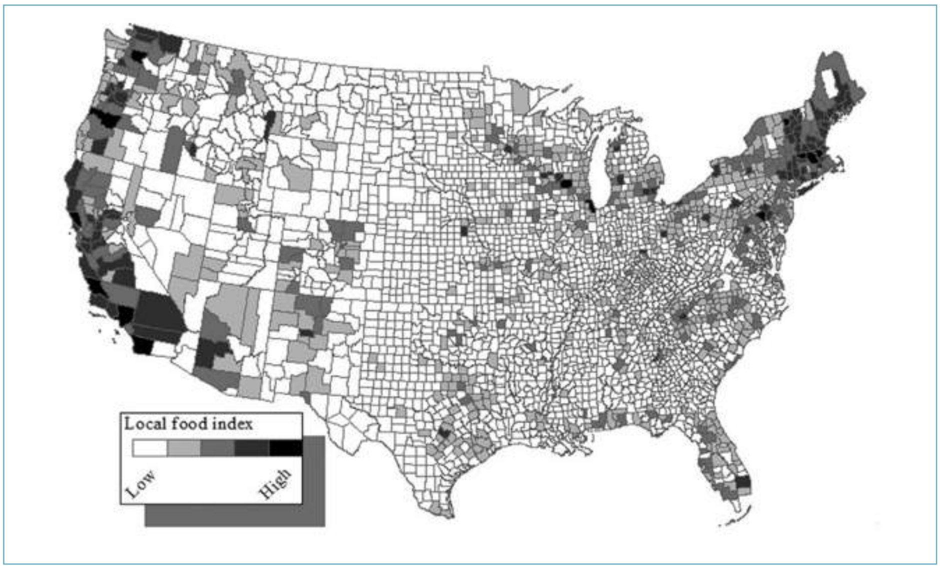

Figure 14: A simple mapping of the local food index (Deller et al. 2017)

61 Bellassen, V., Drut, M., Antonioli, F., Brečić, R., Donati, M., Ferrer-Pérez, H., Gauvrit, L., Hoang, V., Knutsen Steinnes, K., Lilavanichakul, A., & Majewski, E. (2021). The carbon and land footprint of certified food products. *Journal of Agricultural & Food Industrial Organization*, *19*(2), 113–126. https://doi.org/10.1515/jafio-2019-0037
62 Deller, S. C., Lamie, D., & Stickel, M. (2017). Local foods systems and community economic development. *Community Development*, *48*(5), 612-638. https://doi.org/10.1080/15575330.2017.1373136

To further investigate these patterns, the authors analysed the concentrations of local food activity at the county level to identify geographic "hot" and "cold" spots. The goal was to determine if there were clusters of counties with significantly higher or lower concentrations of local food activity. The results of the analysis (Figure 15) indicate the presence of spatial clusters of high and low concentrations of local food activity. These clusters provide insights into the geographic distribution of local food initiatives and include statistical inferences about these spatial patterns.

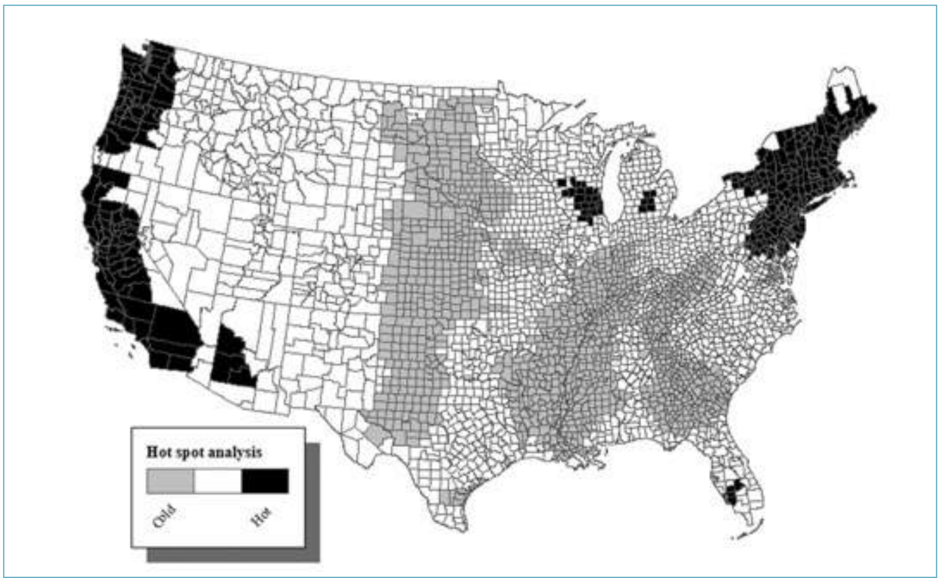

Figure 15: Local foods index spatial clustering (Deller et al 2017)

7. AGRICULTURAL LAND

From a PED perspective, agricultural land can be assessed using two approaches:
1. The potential and potentially irreversible loss of farmland due to PED building activities
2. The availability of cultivation space for food within the PED (perhaps in the form of "urban gardening") to increase food security and reduce emissions for food production and delivery

Here, agricultural land per inhabitant is an important criterion for PED implementation.[63] Urban gardening, particularly the use of agricultural land within cities, is significant. First, it allows for the cultivation of fresh, locally grown produce, promoting access to nutritious food and reducing dependence on long-distance transportation and its associated carbon emissions. Second, urban farming contributes to food security by creating resilient and diverse food systems that can withstand disruptions in the global food supply chain.

Additionally, urban agricultural land helps to enhance biodiversity and mitigate the urban heat island effect by providing green spaces and promoting the preservation of ecosystems within cities. Moreover, gardening encourages community engagement and social interaction, fostering a sense of belonging and well-being among residents. Lastly, urban agricultural land can serve as an educational platform, promoting environmental awareness, sustainable practices, and the importance of healthy eating habits for individuals of all ages. Agricultural land per capita in Europe is shown on Figure 16. At the global level, per capita agricultural land use is now less than half of its value in 1961.

Figure 16: Agricultural land per capita in Europe (2020)[64]

"Urban farming" can be considered in conjunction with PEDs despite being a less common term in the literature. Typically, urban farming involves food production in or close to urban regions.[65] Although urban farming focuses on food production, the use of green areas is of central importance.

63 Klein Goldewijk, K., Beusen, A., Doelman, J., & Stehfest, E. (2017). Anthropogenic land use estimates for the Holocene–HYDE 3.2. *Earth System Science Data*, *9*(2), 927-953.
64 *Our World in Data*. (n.d.). Our World in Data. https://ourworldindata.org/
65 Bailkey, M., & Nasr, J. (2000). From Brownfields to Greenfields: Producing Food in North American Cities, *Community Food Security News*. Fall 1999.

Building roofs are a common target for growing food (Figure 17).[66,67] Rooftop growing is a common strategy in the cities with high population densities.[68] However, this conflicts with recreational activities and energy production. Combining these uses is possible but can be costly.

Urban Food Production (UFP) initiatives are expanding globally to enhance food supplies while promoting sustainable cities. One study developed a sustainability framework for UFP by evaluating stakeholders' perspectives through participatory methods and network analyses.[69] Two workshops were conducted in Bologna, Italy, where stakeholders identified environmental, economic, and social sustainability elements of UFP. The bottom-up approach revealed a comprehensive vision of sustainable UFP, emphasizing certain sustainability elements and key considerations for policy-making while highlighting the trade-offs and synergies among sustainability dimensions. UFP's multi-scalar nature suggests that specific policies can align with global schemes such as the United Nations' Sustainable Development Goals while fostering local democracy and social equity.

Figure 17: BIGH (Building Integrated Greenhouses) Farms implementation[70]

The Ang Mo Kio rooftop carpark farm in Singapore promotes high quality, locally grown, and safe food with the lowest possible footprint (Figure 18).[71] The farm uses hydroponics and smart farming to produce leafy greens, tomatoes, strawberries, and fresh herbs. The farm was developed to promote urban farming and enable the cultivation of fresh vegetables within the city. It incorporates various cultivation systems such as vertical gardens, hydroponic setups, and rooftop gardens. The project serves as an example of utilizing unused urban spaces for agricultural purposes and contributes to the city's food supply and sustainability.

66 Juras, P. (2022). Positive aspects of green roof reducing energy consumption in winter. *Energies, 15(4), 1493.*
67 Borràs, J. G., Lerma, C., Mas, Á., Vercher, J., & Gil, E. (2022). Contribution of green roofs to energy savings in building renovations. *Energy for Sustainable Development, 71*, 212-221
68 Hui, S. C. (2011). Green roof urban farming for buildings in high-density urban cities. The 2011 Hainan China World Green Roof Conference, Hainan (Haikuo, Boao and Sanya), China, 18-21 March 2011, p. 1-9.
69 Sanyé-Mengual, E., Orsini, F., & Gianquinto, G. (2018). Revisiting the Sustainability Concept of Urban Food Production from a Stakeholders' Perspective. *Sustainability, 10*(7), 2175. https://doi.org/10.3390/su10072175
70 *Notre projet – BIGH*. (n.d.). https://bigh.farm/notre-projet/
71 *Sustenir Agriculture - An urban farm using modern technology | SFA*. (n.d.). https://www.sfa.gov.sg/fromSGtoSG/farms/farm/Detail/sustenir-agriculture


Figure 18: The Ang Mo Kio rooftop carpark farm in Singapore[72]

Several studies have focused on the social aspects of urban farming.[73,74] These studies conclude that informing people about the positive benefits of space for agriculture is key to their success.

Agricultural practices are often not considered in the context of PEDs but urban agriculture is part of sustainable urban development and supports food security of the region.[75] These ideas could be considered as a part of global goals of PED development and implementation. Specifically, the legal and economic aspects of urban agriculture are central to sustainable urban development strategies.[76]

FOODMET[77], the new food hall at the Abattoir PED is a showcase for commercial urban agriculture. BIGH sca, a Belgian company, was selected by Abattoir to develop and operate the FOODMET rooftop urban farm. Since 2016, the Foodmet rooftop farm has provided an economically successful and efficient way to provide high quality fresh fish and produce with no antibiotics and pesticides. The project includes 2000 m² of greenhouse space and an equivalent area of open air gardens, creating value for the district and energy performance of the building.

72 Terrence. (2019). Ang Mo Kio rooftop carpark farm to grow four tonnes of vegetables monthly. *Urban Green Lab*. https://ugl.sg/2019/03/08/ang-mo-kio-rooftop-carpark-farm-to-grow-four-tonnes-of-vegetables-monthly/
73 Grebitus, C., Chenarides, L., Muenich, R., & Mahalov, A. (2020). Consumers' perception of urban farming—An exploratory study. *Frontiers in Sustainable Food Systems, 4*, 79
74 Yusoff, N. H., Hussain, M. R. M., & Tukiman, I. (2017). Roles of community towards urban farming activities. *Planning Malaysia 15*(1), 271-278.
75 Barthel, S., Isendahl, C., Vis, B. N., Drescher, A., Evans, D. L., & van Timmeren, A. (2019). Global urbanization and food production in direct competition for land: Leverage places to mitigate impacts on SDG2 and on the Earth System. *The Anthropocene Review, 6*(1-2), 71-97
76 Li, D., Zhong, W., & Chen, Y. (2022). The Role of Farmland Titling in Urban Agricultural Resilience: Evidence from Metropolitan Guangzhou, China. *Sustainability, 14*(23), 15781.
77 *Abattoir's Urban Farm pilot project*. (n.d.). Abattoir. https://www.abattoir.be/en/abattoir-s-urban-farm-pilot-project

8. CLIMATE NEUTRAL MUNICIPALITIES

To achieve climate neutrality in municipalities, several factors come into play. Larger municipalities with intensive land use and high population densities are typically unable to meet their own energy requirements with local renewable energy strategies, whereas smaller and rural municipalities typically have more renewable potential in relation to their energy demands. In fact, the question arises whether larger municipalities, which are typically economic and industrial centres and not only produce for themselves but essentially for the entire country, can and should be expected to achieve balances of energy and emissions.

One approach to remedy this disparity is to distribute demand and supply potentials across the country to achieve climate neutrality at the national scale. Smaller municipalities with an energy surplus can offset larger municipalities. The following paragraphs presents this approach, using a small- to medium-sized Austrian municipality as an example. The approach consists of the following steps:

1. Compile national sectoral energy consumption data
2. Quantify measures to reduce energy consumption in municipalities (e.g., energy-efficient renovations of buildings, promotion of sustainable mobility, and so on)
3. Estimate the renewable energy potentials of all municipalities
4. Establish national target values for renewable energy production, energy savings, and energy demand based on future climate-neutral energy scenarios and policy goals
5. Establish municipal target values for energy demand savings by considering the potentials of renewable energies and specific characteristics of each municipality

Through a comprehensive focus on municipalities, a climate-neutral country scenario can be broken down into customised municipal climate goals that collectively achieve the national scenario.

ENERGY CONSUMPTION

To determine potential energy savings and future energy demand, and to establish energy consumption targets for each municipality, it is necessary to establish a baseline of current energy consumption. Energy consumption data is available from national inventories for the most important sectors including households, agriculture and forestry, industry and production, services, and transport and mobility. In Austria, the national inventory is the Austrian Energiemosaik.[78]

78 *Energiemosaik Austria*. (n.d.). Energiemosaik Austria. https://www.energiemosaik.at/

MEASURES TO REDUCE ENERGY CONSUMPTION

The municipal energy saving potential can then be derived using energy saving factors from the literature for each sector. For example, in the building sector, energy savings can be achieved through renovations and optimization of heating and hot water systems, with the energy saving factor representing the ratio of energy consumption before and after the renovation. In the industry and production sector, energy savings can be achieved through process optimization and automation, the use of more energy-efficient equipment, and energy-saving lighting. In the mobility sector, similar scenario studies serve as the basis to determine the savings potential. The resulting energy saving factor is based on the ratio of energy consumption before and after the electrification and improvement of mobility services.

ESTIMATING RENEWABLE ENERGY POTENTIALS

Estimating the renewable energy potentials of municipalities involves assessing the potential for renewable energy production within the spatial boundaries of a specific municipality. This includes collecting and determining annual yields from literature for renewable energy systems such as photovoltaics (PV), wind power (WP), hydropower (HP), biomass (BM), solar thermal (ST), and near-surface geothermal energy (GT). Typically, only a fraction of the municipal renewable energy potential needs to be realized to achieve a national climate-neutral scenario. The key is to share this fraction equally across all potential spaces rather than being restricted to municipal boundaries. For example, municipality A and municipality B have an equal energy demand of 10 and a generic renewable potential of 15 and 45 respectively. A climate neutral city approach would require both municipalities to realize a renewable energy potential of 10. This means that they both need to realize the same share of the total required energy of 20/60, or 1/3. Thus, municipality A would realize 5/15 and have a net-negative energy balance of -5 and municipality B would realize 15/45 resulting in a net energy balance of +5, given that it has a greater initial potential for renewables.

To this end, the municipal potentials need to be correlated with suitable reference or scaling areas that represent similar spatial potentials and can be used to allocate the national scenario requirements. For this, areas such as arable land, forested area, local solar radiation, local wind speeds, and water resources at the municipal (m), county (c), and state (s) NUTS classification levels can be used. But the allocation could also employ different or more detailed reference areas. The formulas in Figure 19 represent these calculations of renewable energy potentials at the municipal level:

- The wind power potential for the municipality is calculated as the available cultivated land in the municipality in relation to the total cultivated area of the county.
- The photovoltaic potential is based on the roof area in the municipality and the average yield of roof-mounted photovoltaics.
- The near-surface geothermal energy potential for the municipality is determined by the near-surface geothermal energy potential of the county and allocated according to the area of the municipality in relation to the total area of the county.
- The hydropower potential for the municipality is determined by the hydropower potential of the county and allocated by the relative area of the municipality in relation to the total area of the county.

- The solar thermal potential is determined by multiplying the roof area in the municipality by the specific yield value typical for solar thermal.
- The biomass potential is allocated with the forested area in the municipality by an average caloric value for wood.

Figure 19: Geographic allocation parameters and scaling variables for distributing national (underscore c) savings and expansion targets at the municipal level (underscore m)

SETTING TARGETS FOR ENERGY SAVINGS AND RENEWABLE POTENTIALS

Various future energy scenarios provide sectoral targets for renewable energy production, energy savings, and energy demand, according to established political timeframes. For example, the Austrian government is targeting the year 2040.[79] These sectoral targets can be realised by aggregating the targets of all individual municipalities. The scaling and allocation of renewable potential realization targets and saving targets are calibrated with these national targets.

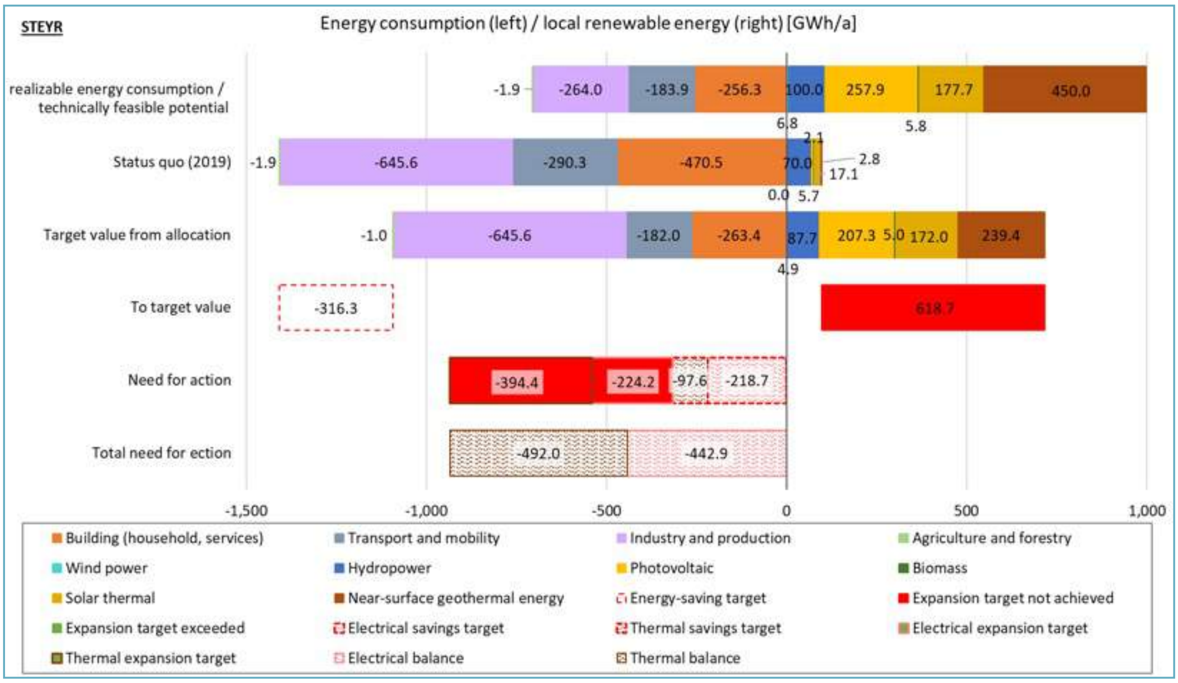

Figure 20: Energy balance and need for action for an example municipality

79 Schneider, S., Zelger, T., & Klauda, L. (2020). Überlegungen zur Frage, welcher Anteil erneuerbarer Energie 2050 in Österreich lokal aufgebracht werden muss. In *Symposium Energieinnovation TU Graz, ENERGY FOR FUTURE Wege zur Klimaneutralitaet, TU Graz.(Available online)*. https://www.tugraz.at/fileadmin/user_upload/tugrazExternal/4778f047-2e50-4e9e-b72d-e5af373f95a4/files/lf/Session_A3/135_LF_Schneider_Simon.pdf

ALLOCATIVE DISTRIBUTION

The allocation of the national scenario targets to individual municipalities can be determined based on their respective share to the overall expansion or energy savings potential (Figure 20). In other words, the allocation is performed so that each municipality has to realize the same share of their respective potential rather than achieving the same absolute balance. This allocation method considers the specific characteristics of each municipality by aligning its potential contribution to the target with the assessed potential specific to its location. The distribution approach ensures a balanced target achievement by allowing municipalities with surplus potential to offset those with lower potential.

These targets should only be understood as guidelines to establish a quantitative relationship with the achievability at the national level, rather than as strict requirements for how to achieve an overall balance. As a basis for discussion, the following overview was developed, summarizing the identified and extrapolated figures for each municipality.

This example municipality demonstrates the high energy demand from the industry and production sector, which does not have any energy savings targets until 2040 in the national allocation scenario. Instead, the main focus of the need for action comes from the expansion side where PV, ST and GT have the largest unrealised potentials. Significant savings are needed in the mobility and building sectors.

The above individual energy balances for the selected municipality of Steyr, a city of approximately 40,000 inhabitants, show the difference between status quo and sectoral targets, denoted as target values. This can be further aggregated into a need for action by combining differences in savings and renewable expansion and differentiating between thermal and electric energy. This is important to facilitate political discussions and facilitate path independence to achieve these targets. For example, a municipality could opt to change measures from one sector to another, if it is politically or economically more feasible, as long as the overall target is reached.

The resulting distributions can be visualized in geospatial potential and target maps, as shown in Figure 21. This illustrates how national targets for a renewable energy balance vary across municipalities when considering local expansion and reduction potentials. Larger urban areas tend to have lower requirements for the balance targets to be considered climate neutral cities.

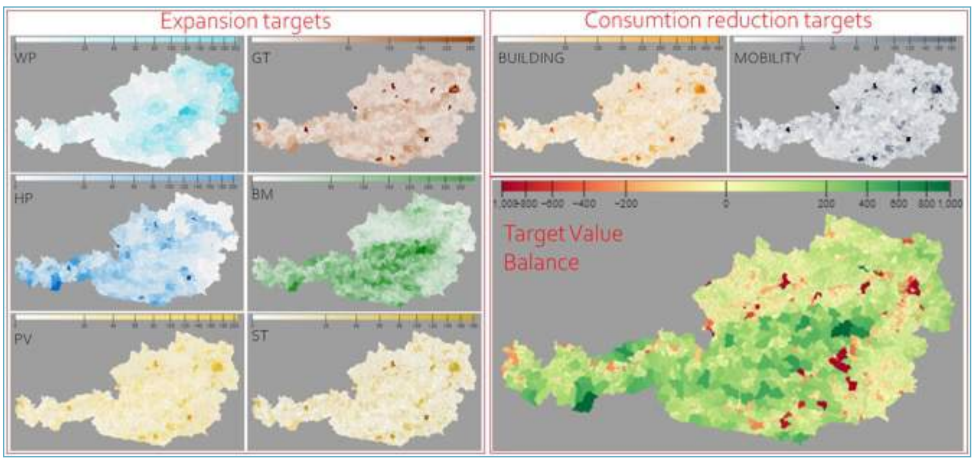

Figure 21: Geographic representation of the expansion targets and consumption reduction targets, as well as the resulting differentiated energy balance target of the municipality depending on their local potentials

9. QUALITY OF LIFE PER GHG EMISSION

The PED KPI to address 'Quality of Life per Greenhouse Gas Emission' is not readily available for assessment purposes yet. However, such a KPI would be helpful to leverage the connections between two sub-indicators, 'Quality of Life' and 'Greenhouse Gas Emissions'. These concepts are addressed in the following paragraphs.

'Quality of life' is a complex term that includes different aspects of daily life of residents: health, economic standard of living, demands and availability of resources, psychological conditions, and so on. Quality of life is central to PED implementation in multiple ways. For example, with respect to demand and availability of resources, "resources" can mean energy required for heating/cooling or electricity for daily needs. In turn, balances between energy demand and supply are the most common way to characterize PEDs and are closely related to quality of life.

Public health is one aspect of quality of life and there are multiple studies on how this relates to energy issues. For example, Mizdrak et al. (2019) highlight the complex problem of shifting short vehicle trips to walking and cycling as a factor of the improvement of human health together with a reduction in green-house gas emissions.[80] Other studies connect mobility to quality of life and PED development.[81] For example, the adoption of electric vehicles can decrease GHG emissions and air pollution, resulting in higher travel satisfaction, health improvement of citizens and, thus, quality of life improvements.[82]

'Greenhouse Gas Emissions' are naturally an integral part of PED assessment due to its conceptual understanding.[83,84,85] Implementing renewable energy technologies to decrease greenhouse gas emissions is associated with energy poverty and quality of life. Renewable energy is a fast and effective way to address energy demand while decreasing energy poverty and achieving sustainable development goals.[86,87,88] This is also related to economic poverty that hampers efforts to implement renewable energy strategies. There is a need for more studies on the relationship between energy poverty and greenhouse gas emissions.

80 Mizdrak, A., Blakely, T., Cleghorn, C. L., & Cobiac, L. J. (2019). Potential of active transport to improve health, reduce healthcare costs, and reduce greenhouse gas emissions: a modelling study. *PLoS One*, *14*(7), e0219316.
81 Castillo-Calzadilla, T., Alonso-Vicario, A., Borges, C. E., & Martin, C. (2022). E-Mobility in positive energy districts. *Buildings*, *12*(3), 264. https://doi.org/10.3390/buildings12030264
82 Pignatta, G., & Balazadeh, N. (2022). Hybrid Vehicles as a Transition for full E-Mobility Achievement in Positive Energy Districts: A Comparative Assessment of Real-Driving Emissions. Energies, 15(8), 2760. https://doi.org/10.3390/en15082760
83 Kleinebrahm, M., Weinand, J. M., Naber, E., McKenna, R., & Ardone, A. (2023). Analysing municipal energy system transformations in line with national greenhouse gas reduction strategies. *Applied Energy, 332*, 120515
84 Cellura, M., Fichera, A., Guarino, F., & Volpe, R. (2022). Sustainable development goals and performance measurement of positive energy district: A methodological approach. In *Sustainability in Energy and Buildings 2021* (pp. 519-527). Springer Singapore.
85 Derkenbaeva, E., Vega, S. H., Hofstede, G. J., & Van Leeuwen, E. (2022). Positive energy districts: Mainstreaming energy transition in urban areas. *Renewable and Sustainable Energy Reviews, 153*, 111782.
86 Zhao, J., Dong, K., Dong, X., & Shahbaz, M. (2022). How renewable energy alleviate energy poverty? A global analysis. *Renewable Energy, 186*, 299-311
87 González-Eguino, M. (2015). Energy poverty: An overview. *Renewable & Sustainable Energy Reviews*, *47*, 377–385. https://doi.org/10.1016/j.rser.2015.03.013
88 Nussbaumer, P., Bazilian, M., & Modi, V. (2012). Measuring energy poverty: Focusing on what matters. *Renewable & Sustainable Energy Reviews*, *16*(1), 231–243. https://doi.org/10.1016/j.rser.2011.07.150

CONCLUSIONS

The purpose of this report was to highlight existing tools and assessment approaches that could be adapted to PED development processes. These approaches were identified through a roundtable discussion with the stakeholders from the TRANS-PED project. The stakeholders identified several assessment needs to support the further development of their specific PEDs. The following sections then summarised insights from related literatures to provide a foundation for an extensive suite of evaluation approaches. In the coming years, it is hoped that these assessment approaches will be adapted to PEDs and used to produce more robust evaluations of PED achievements while also connecting their strong energy ambitions with related agendas of mobility, green infrastructure, waste, food, and climate neutrality.

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