# A Holistic Sustainability Evaluation of Positive Energy Districts—Planetary Boundaries Framing the Transformation of Districts

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**Abstract** The development of districts requires a distinct understanding of the current situation as well as a vision of future districts to be able to develop suitable pathways for a sustainable transition. The concept of Positive Energy Districts (PEDs) is one of the main initiatives in Europe for the clean energy transition in the built environment. While PEDs are mainly heading for the energy transition, little is known how they relate to the holistic concept of planetary boundaries (PB). To be able to build representative methodology for sustainability assessment of PEDs as well as define comparable, measurable, and reliable indicators specifically targeted for the district scale, we take a closer look at the concept of PB in order to analyze how this concept can help to establish a holistic sustainability evaluation of PEDs. Below we present an analysis of two PED concepts to discuss their interrelation with the PB concept. Our research is based on literature and document analysis. We identify the need for a comprehensive understanding of the different aspects impacting the sustainability assessment of PEDs. In this sense, although highly advisable, an integrated and systemic approach to the sustainability assessment of PEDs has still not been consolidated and the main environmental, economic, and social pillars are usually treated as separate spheres with limited interlinked issues.

**Keywords** Planetary boundaries · Sustainability evaluation · Positive energy districts

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# 1 Introduction

Several initiatives in Europe aim for the clean energy transition in the built environment. The concept of Positive Energy Districts (PEDs) is advocated by energy policies and international working groups to accelerate the decarbonization of urban areas and promote the potential for scalability between cities. To be able to plan a district with a positive perspective of its attributes, it is mandatory to establish a new framework based on a list of key performance indicators (KPIs). Planetary boundaries (PB) define the boundaries of the "planetary playing field" for humanity if major human-induced environmental change on a global scale is to be avoided. Transgressing one or more PB could be highly damaging or even catastrophic due to the risk of crossing thresholds that trigger non-linear, abrupt environmental change within continental- to planetary-scale systems. Identifying the PB can therefore be used as an approach towards a new framework for PEDs based on a good understanding of the PB, i.e., towards an estimation of the safe space for human development. In this sense, it is interesting to study these PB in relation to district developments, namely, the new concept of PEDs.

In this paper, we address the need for a comprehensive understanding of the different aspects impacting the sustainability assessment of PEDs. In this sense, although highly advisable, an integrated and systemic approach to the sustainability assessment of PEDs has still not been consolidated and the main environmental, economic, and social pillars are usually treated as separate spheres with limited interlinked issues. To be able to build representative methodology for sustainability assessment of PEDs as well as define comparable, measurable, and reliable indicators specifically targeted for the district scale we take a closer look at the concept of PB to find out how this concept can help to establish a holistic sustainability evaluation of PEDs. There are three important key questions:

- Can the concept of PB be used when planning PEDs?
- How does the PED concept relate to PB?
- Which other boundaries are important for PEDs?

# 2 Background

## *2.1 Positive Energy District Activities*

PEDs are the main focus of several activities on a European scale as well as the focus of international research by the International Energy Agency Energy in Buildings and Construction Annex 83 "Positive Energy Districts". Although a common and comprehensive definition is still being widely discussed, it is generally accepted that Positive Energy Districts are specific areas with annual net zero energy import and net zero $CO_2$ emissions, working towards an annual local surplus production of renewable energy. These districts are a key part of the transformative process from carbon-intensive cities towards sustainable urban development through a diverse set of solutions, including technological ones (building interaction, ICT, mobility, low-carbon building materials and technologies) as well as legal, economic and social ones (Annex 83).

PEDs are significant for their innovative capacity, at the same time they also present, challenges as well as opportunities for local and global sustainable development (Cost Action PED-EU-NET). The actual impact of PEDs over local sustainable development targets, meanwhile, remains uncertain. This is mainly because "*intangible elements abound in the environmental, social, cultural and institutional perspectives of sustainable development beyond the economic one and in the open, complex and dynamic ecosystems that constitute the cities in which these technologies are deployed*" (Set Plan). To support monitoring of relevant projects and initiatives, Key Performance Indicators (KPIs) can be useful tools to evaluate the progress of PEDS or smart city strategies in general as, when chosen correctly make it possible to model and describe complex phenomena through quantitative and qualitative indicators (EU WG) effectively. In a recent study, the sustainability assessment of PEDs was analyzed (Guarino et al. 2021). It was found that the field is still largely fragmented despite the fact it is fundamental to support the clean energy transition of the built environment.

## 2.2 PB Thresholds

PB is a concept describing earth system processes that contain environmental boundaries. It was proposed in 2009 by Johan Rockström from the Stockholm Resilience Centre and Will Steffen from the Australian National University (Rockström et al. 2009a). The framework is based on scientific evidence that human actions have become the main driver of global environmental change since the Industrial Revolution. The intention was to define a "*safe operating space for humanity*" for the international community, including governments on all levels, international organizations, civil society, the scientific community, and the private sector, as a precondition for sustainable development.

According to the PB concept, "*transgressing one or more planetary boundaries may be deleterious or even catastrophic due to the risk of crossing thresholds that will trigger non-linear, abrupt environmental change within continental-scale to planetary-scale systems*" (Rockström et al. 2009a). Earth system process boundaries mark a safe zone for the planet to the extent that they are not crossed. As of 2009, two boundaries had already been crossed, while others were in imminent danger of being crossed (Rockström et al. 2009a). However, an update from Steffen et al. (2015) suggests that four of the boundaries have been crossed: "*climate change, loss of biosphere integrity, land-system change, altered biogeochemical cycles (phosphorus and nitrogen)*" (Steffen et al. 2015).

In the PB concept, the threshold, or tipping point, is the value at which a very small increase in a control variable (like $CO_2$) triggers a larger, possibly catastrophic,

**Table 1** PBs and their relevance for PEDs (Rockström et al. 2009a)

| Earth-system process | Control variable | Threshold crossed |
|---|---|---|
| 1. Climate change | Atmospheric carbon dioxide concentration (ppm) | Yes |
| | Alternatively: Increase in radiative forcing ($W/m^2$) since the start of the industrial revolution (~1750) | Yes |
| 2. Biodiversity loss | Extinction rate (number of species per million per year) | Yes |
| 3. Biogeochemical | (a) anthropogenic nitrogen removed from the atmosphere (millions of tons per year) | Yes |
| | (b) anthropogenic phosphorus going into the oceans (millions of tons per year) | No |
| 4. Ocean acidification | Global mean saturation state of calcium carbonate in surface seawater (omega units) | No |
| 5. Land use | Land surface converted to cropland (percentage) | No |
| 6. Freshwater | Global human consumption of water ($km^3/yr$) | No |
| 7. Ozone depletion | Stratospheric ozone concentration (Dobson units) | No |
| 8. Atmospheric aerosols | Overall particulate concentration in the atmosphere, on a regional basis | Not yet quantified |
| 9. Chemical pollution | Concentration of toxic substances, plastics, endocrine disruptors, heavy metals, and radioactive contamination in the environment | Not yet quantified |

change in the response variable (global warming) through feedback to the natural earth system itself. The threshold points are difficult to locate because the earth system is very complex. Instead of defining the threshold value, a range was established where the threshold is supposed to lie inside it. The lower end of that range is defined as the boundary. Therefore, it defines a "safe operating space", in the sense that as long as we (mankind) are below the boundary, we are below the threshold value (Table 1). If the boundary is crossed, we enter a danger zone (Rockström et al. 2009a).

## *2.3 Interaction Between Boundaries*

A PB may interact in a manner that changes the safe operating level of other boundaries. Rockström et al. (2009a) did not analyze such interactions but they suggested that many of these interactions will reduce rather than expand the proposed boundary levels (Rockström et al. 2009a). For example, the land use boundary could shift downward if the freshwater boundary is breached, causing lands to become arid and unavailable for agriculture. At a regional level, water resources may decline in Asia if deforestation continues in the Amazon. Such considerations suggest the need for "*extreme caution in approaching or transgressing any individual planetary boundaries*" (Rockström et al. 2009b).

# 3 Methodology

We collected data from literature on the PB concept and compared it with data collected from two PED concepts in Norway and Switzerland. Two PED concepts were analyzed relating to the methodology development and KPIs used to evaluate PEDs. These key aspects were used to analyze the PED framework (in the Norwegian and Swiss PED) relation to PB. As a result, those measures were identified which support the PB concept and those which should be analyzed further.

## *3.1 Two PED Concepts and Their Sustainability Assessments*

Two PED concepts are presented, the 2000-W Site (2000WS) from Switzerland and the Zero Emission Neighborhood (ZEN) concept from Norway (Haase 2021; Wiik et al. 2018).

# 4 2000-W-Site

The 2000-W-Site (2000WS) is a new concept developed in Switzerland resulting in new forms of settlements (Haase 2021). It has gained a reputation for energy efficiency, renewable energies, and climate friendliness and reflects the values of a responsible society. The core idea of the 2000-W Site is an ongoing evaluation process of a site's sustainability in terms of energy consumption and production in development, planning, implementation, and operations of the district. Certificates that document the status of development/sustainability progress are issued for a limited time period and must be renewed periodically. They are awarded in two stages: As a "site under development" until at least half of the total living space is in use, and after completion as a "site in operation". The concept of a 2000WS takes an integrative view of the entire site rather than individual buildings by depicting the whole living environment. The subject areas of the criteria to evaluate 2000WS are shown in Table 2.

# 5 Zero Emission Neighborhoods

Already in 2008, the Norwegian Parliament decided that Norway should become "carbon neutral" by 2050 and recently Norway enhanced its nationally determined contribution under the Paris Agreement to reduce emissions by at least 50% and as much as 55% compared to 1990 levels by 2030 (Norwegian Ministry of Climate and Environment 2019).

**Table 2** Evaluation criteria of the 2000WS certification scheme

| Subject area | Key performance indicators |
|---|---|
| 1. Management system | Structure of area ownership for planning, realization and operations, goal agreement, long-time monitoring system, contract for reaching goals, monitoring operational energy and mobility services, quality management system |
| 2. Communication, cooperation, participation | Stakeholder analysis and involvement, the possibility for dialogue and to exchange feedback, participative rules, user-related information and specific offers on energy and mobility-related topics |
| 3. Site utilization and urban planning | Integration in urban development, integrated district, and outdoor concept, urban climate strategy with a focus on ventilative cooling, avoidance of heat islands, semi-public spaces on the ground floor, common spaces inside, on roofs and loggias, public access to green spaces with high "staying" quality, on-site or nearby offers for goods and services tailored to user needs |
| 4. Supply and waste disposal | Locally produced high ecological quality energy, local renewable heat and electricity generation and self-consumed electricity, end energy with high ecological quality (100% renewable of which 50% is eco-labeled electricity (nature made star or equal), tailor-made water concept incl. monitoring drinking water with a feedback loop and a phase-conform waste management concept with monitoring, feedback and an improvement loop |
| 5. Buildings | Mandatory LCC, participative quality competition for sites within the urban setting, optimized construction, building operations, and mobility in terms of sustainable building principles, moderate (low) people per area, and flexible use of onsite areas |
| 6. Mobility | Minimized parking areas with operating concepts that cross-finance public transport, optimized bicycle parking areas with good access and high quality, good footpath and bicycle lane networks, good connections to other footpath networks and bicycle lanes, barrier-free, attractive offers for public transport with well-designed stops and connections, combined mobility concepts for users, car-sharing pools with user-centric combination offers |

There is no specific regulation for PEDs in general so the policy framework consists of different laws and regulations, guiding principles, white papers, and standards that influence the implementation of PEDs. While municipal goals are set on regional and urban scales through climate and energy plans, goals for buildings and blocks of buildings are set by their individual owners. Setting energy and emission goals at an intermediate level between city and buildings is a new approach in Norway and was mainly developed through the research center for Zero Emission Neighborhoods in Smart Cities, which is a frontrunner in developing this new research perspective in Norway. A Zero emission neighborhood aims to reduce its

**Table 3** Evaluation criteria of ZEN demo sites (Wiik et al. 2018)

| Criteria | Key performance indicators |
|---|---|
| GHG emission | Total GHG emissions in $tCO_2eq/m^2BRA/a$; $kgCO_2eq/m^2BAU/a$; $tCO_2eq/capita$<br>GHG emission % reduction compared to the base case |
| Energy | Energy efficiency in buildings (Energy efficiency in buildings, Net energy need in $kWh/m^2BRA/a$; Gross energy need in $kWh/m^2BRA$)<br>Energy carrier (Energy use in kWh/a; Energy generation in kWh/a; Delivered energy in kWh/a; Exported energy in kWh/a; Self-consumption in %; Self-generation in %; Color coded carpet plot in kWh/a) |
| Power/load | Power/load performance (Netload early profile in kW; Net load duration curve in kW; Peak load in kW; Peak export in kW; Utilization factor in %)<br>Power/load flexibility (Daily net load profile in kW) |
| Mobility | Mode of transport (% share)<br>Access to public transport (Meters; Frequency) |
| Economy | Life cycle cost (LCC) (NOK; $NOK/m^2BRA/a$; $NOK/m^2BAU/a$; NOK/capita) |
| Spatial qualities | Demographic needs and consultation plan (Qualitative)<br>Delivery and proximity to amenities (Number of amenities, Meters (distance from buildings); Public space (Qualitative) |

direct and indirect GHG emissions to zero over its lifespan. At the time of writing, a neighborhood is defined within the ZEN center as a group of interconnected buildings with associated infrastructure, located within a confined geographical area (Wiik et al. 2018) The ZEN definition is still under development but a framework of KPIs in six respective categories, namely, GHG emissions, energy, power/load, mobility, economy, and spatial qualities, is already in place (see Table 3).

Similar to the 2000WS concept, Norwegian districts will be assessed using these KPIs with a multi-criterial analysis. The results document the status of development towards zero emission neighborhoods and will help stakeholders involved to adapt plans, designs, and operating assets towards more sustainable patterns.

## 6 2000-W-Site and ZEN—Two PED Concepts and Their Sustainability Assessment

From the key performance indicators in PEDs (Tables 2 and 3), it is clear that two main indicators can be related to PB in PEDs. Firstly, to be able to mitigate further degradation of the climate system, it is mandatory to radically reduce GHG emissions. This not only includes reducing the energy consumption through conservation and efficiency but it also means switching to clean energy sources as well as reducing embodied carbon throughout supply chains and designing in general terms without waste generation.

PEDs as well as larger built environments also contribute to GHG emissions by embodied carbon in the built environment. Construction material use and its related embodied emissions as well as mobility both contribute to operational and embodied GHG emissions. IF green spaces are integrated into PEDs they can have a positive influence on reducing surface temperatures (urban heat island effect) and in addition on the operational energy and GHG emissions associated with cooling buildings and spaces in PEDs. In PED buildings, operational energy in both new builds and retrofits can be improved with efficient ventilation systems and passive and low temperature heating and cooling. In addition, efficient and natural lighting strategies and optimized building envelopes in co-design with efficient appliances have shown the potential to reduce operational energy. Embodied GHG emissions on the other hand can be minimized by reducing material use and choosing nature-based materials and circular processes. In PED, operating performance can be further improved with design considerations and innovation, and material demand can be reduced through increased efficiency. This requires that materials must be optimized throughout their lifecycle to reduce carbon in terms of their origin, extraction, processing and end of life considerations. This also includes material innovations such as low-carbon concrete and strategies such as designing for reuse.

One possibility for material choice in PED planning and construction processes is sustainable material sourcing such as timber sourced from sustainably managed, biodiverse plantation forests to avoid the degradation of old growth areas to maximize carbon sequestration. Where useful, fast-growing bio-based materials such as bamboo and hemp can be used as alternatives to timber.

Secondly, PEDs have a direct impact on land use change through constraints on urban growth by making better use of already converted land to prevent urban sprawl and land and forest degradation. How transport and infrastructure are planned directly influences further deterioration of the quality of forest land, especially of old forests. City governments and utilities can develop PED policies and invest directly in protecting and restoring their local forested catchments to improve the delivery of ecosystem services, including improving water quality and seasonal river resilience: lower flood risk downstream; temperature control; improve biological diversity and increase cultural value.

## 7 Discussion

As the focus of this work was to take a closer look at the concept of PB to find out how this concept can help to establish a holistic sustainability evaluation of PEDs, we found that the concept of PB can be used when planning PEDs. When analyzing the key performance indicators of PED concepts (Table 4), it became clear that there are two PBs that are directly related to the indicators used in the PEDs:

- Climate change
- Land use

**Table 4** PB in PEDs

| PB | ZEN | 2000 W areal |
|---|---|---|
| *A. Climate change* | | |
| $CO_2$ concentration in the atmosphere <350 ppm and/or a maximum change of +1 $W/m^2$ in radiative forcing | Total GHG emissions in $tCO_2eq/m^2BRA/a$; $kgCO_2eq/m^2BAU/a$; $tCO_2eq$/capita, GHG emission reduction % reduction compared to the base case | The basis forms the calculation that for every person on earth, 2000 Watts of continuous power (primary energy) are available. The $CO_2$ emissions caused by this level of energy consumption must not exceed 1 ton per person per year |
| | Zero emission in all phases not only operations, building on LCA and incorporating embodied emissions; Assessment of materials with the help of the Environmental Product Declaration (EPD) | Optimized construction, building operation and mobility in terms of sustainable building principles |
| | Energy efficiency in buildings (Energy efficiency in buildings, Net energy need in $kWh/m^2BRA/a$; Gross energy need in $kWh/m^2BRA$) | Optimized construction, building operation, and mobility in terms of sustainable building principles |
| | Energy carrier (Energy use in kWh/a; Energy generation in kWh/a; Delivered energy in kWh/a; Exported energy in kWh/a; Self-consumption in %; Self-generation in %;color coded carpet plot in kWh/a) | |

(continued)

**Table 4** (continued)

| PB | ZEN | 2000 W areal |
|---|---|---|
| | Renewable energy Peak load in kW; Peak export in kW; Utilization factor in %) | Renewable energy onsite, locally produced high ecologica Renewable energy onsite, locally produced high ecological quality energy, local renewable heat and electricity generation and self-consumed electricity, end energy with high ecological quality (100% renewable of which 50% is eco-labeled electricity (nature made star or equally),l quality energy, local renewable heat and electricity generation and self-consumed electricity, end energy with high ecological quality (100% renewable of which 50% is eco-labeled electricity (nature made star or equally) |
| | Mode of transport (% share);Access to public transport (Meters; Frequency) | Minimized parking areas with operating concepts that cross-finance public transport (incl. differentiated user profiles), optimized bicycle parking areas with good access and high quality, good footpath and bicycle lane networks onsite, good connections to other footpath networks and bicycle lanes, barrier-free, attractive offers for public transport with well-designed stops and connections, combined mobility concepts for all users, car-sharing pools with user-centric combination offers |
| *B. Land use* | | |
| <15% of the ice-free land surface under cropland | Requirements to establish spatial qualities that do affect the sustainable behavior of users of the neighborhood; set of KPIs on urban spatial patterns | Integration in urban development, integrated districts, and outdoor concepts, urban climate strategy with focus on ventilative cooling and avoidance of heat islands, semi-public spaces on the ground floor, common spaces inside, on roofs and loggias, public access to green spaces with high "staying" quality, on-site or nearby offers for goods and services tailored to user needs |
| | Assessment of materials with the help of the Environmental Product Declaration (EPD) to assess GHG | Sustainable materials and circular principles, a phase-conform waste management concept with monitoring,feedback and an improvement loop |
| | KPIs on density to reduce land use | Sustainable materials and circular principles, a phase-conform waste management concept with monitoring, feedback and an improvement loop |

In the following, we discuss further how the PED concept relates to PB and which other boundaries might be important when planning PEDs.

### 7.1 How Does the PED Concept Relate to PB?

Climate change has significant consequences for all socio-ecological systems and as we have seen has a cascading effect on other boundaries.

Reducing GHG emissions is key to returning to a safe operating space. PEDs and cities when planned with PB in mind have the potential to reduce their GHG emissions by drastically reducing operational and embodied GHG emissions. Integrating green spaces into PEDs can help to capture and store $CO_2$ to reduce the urban heat island effect and thus energy demands related to cooling.

The other element is land use area, which is obviously a central element of PEDs. Only the transformation of existing districts would not use land, all other developments use land and thus contradict the fifth PB. Eventually, the use of green roofs (and facades) could be counted as cropland and have a positive influence.

### 7.2 Which Other PB Are Important for PEDs?

Freshwater:

Embedding local water cycle considerations in PED planning and design processes can support global freshwater quality. The impact of PEDs on freshwater use can further be enhanced by improving water efficiency and conservation and selecting building materials and products with low water inputs. The resilience of water sources can also be improved by proactively managing or mimicking natural water processes with nature-based solutions.

Biodiversity loss:

PEDs can improve biosphere quality and mitigate further loss by reducing embodied ecological impacts in materials, food, and other products; maximizing the quantity and quality of urban habitats; and planning linear infrastructure to protect, restore, and connect habitats.

Aquatic biodiversity can be influenced by the water quality in PEDs. Reducing contaminated runoff as well as preventing untreated sewage discharge and reducing water use can improve biodiversity in these surroundings.

The urban infrastructure of PEDs has an influence on nutrient flows to balance or close complete cycles. The nutrients in sewage slurry, food, and yard waste can become an added value rather than a cost if appropriately managed. In PEDs, these can be converted into biogas through anaerobic digestion. The produced digestate can be used as a fertilizer and soil amendment to improve soil health, reducing the need for chemical fertilizer. In PEDs, local facilities can be integrated that enable these circular nutrient flows. PEDs can reduce indirect nutrient pollution from agricultural imports through sustainable food sourcing and by scaling up local food production.

Aerosol pollution:

There is the possibility in PEDs to reduce aerosol pollution by mitigating major sources of particulate emissions including the use of fossil fuel combustion for energy, transport, and industry, and minimizing construction and demolition dust. Electrified heating and cooling, transport, cooking, and industry can reduce local emissions in PEDs.

## 8 Conclusions

The discussion highlights the need for a comprehensive understanding of the different aspects impacting sustainability in terms of PB of PEDs.

The study of the two PED cases in Norway and Switzerland showed that both concepts do not focus on the PB. In the case in Norway, a set of KPIs was developed that mainly tries to minimize impact compared to a "base case". Then certain measures can be used to offset the impact (e.g., the renewable electricity produced onsite can be used to offset GHG emissions from the grid). This concept is therefore heading for a better than usual approach and not congruent with the PB approach, which is framing precise thresholds for development. In Switzerland, on the other hand, the PED concept of 2000 WS does not try to stay within the PB. On the contrary, a 2000 W power use is allowed for every citizen. Even though this implies a very small footprint, it allows certain PB to reach and crossover.

There are two aspects that need to be integrated: First, starting with PEDs, there should be a focus on a regenerative model for the built environment that allows us to plan the built environment to stay within the PB. Incorporating PB into environmental and sustainability assessments in PED projects is imperative. This requires PB thresholds to be downscaled to a manageable PED scale.

Secondly, the overshoot of several PB indicates that we need to develop strategies to regenerate the Earth system and how we impact it. This will require a fundamental shift in the way we think about our relationship with the planet. We have to re-think what a balanced human–planet relationship might look like and define PB that limit our impact on the earth system.

In conclusion, the concept of PB can help to establish a holistic sustainability evaluation of PEDs as a framework for the transformation of districts. However, it seems a concerted effort is needed to integrate the nine PB into PED sustainability evaluation schemes. The KPIs used in PEDs need to include the PB if we want to use PED developments to stay within the PB.

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