ZERO CARBON NEIGHBOURHOODS: CREATING NON-COMPLEX INFORMATION FROM COMPLEX DATA

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ABSTRACT

Scotland's commitment to achieving Net Zero by 2045 has led public authorities to align their guidelines with national targets for reducing CO2e emissions. Anderson Bell & Christie Architects, in collaboration with the University of Strathclyde, are developing the Zero Carbon Neighbourhoods (ZCN) Toolkit, a pioneering initiative designed to quantify neighbourhood emissions and offer place-based carbon reduction and sequestration solutions. The ZCN Toolkit aims to support a wide range of stakeholders, including local authorities, community groups, developers, and housing providers, in their efforts to reach net zero, with a particular focus on engaging non-technical audiences.

The project's methodology integrates data collection, stakeholder engagement, and CAD-based modelling to address carbon reduction and sequestration challenges. Data is gathered on neighborhood elements such as operational energy, transport, green spaces, and demographics, forming the basis for models that simulate carbon reduction scenarios. Stakeholder involvement is central, with workshops, surveys, and consultations ensuring that the solutions are co-created and tailored to local needs.

Numerical modeling tools are used to quantify the impact of interventions on emissions, energy efficiency, and carbon sequestration. Effective communication strategies translate complex data into accessible formats like 3D models, infographics, and interactive dashboards, ensuring that non-technical audiences can easily understand and act on the information.

The modeling outputs empower local authorities with guidance for policy development and infrastructure planning, provide community groups with actionable recommendations, and offer housing providers insights into energy-efficient design and sustainable transportation options. The ZCN project exemplifies a holistic, inclusive approach to tackling carbon reduction at the neighborhood level, aiming to catalyze meaningful change towards achieving community carbon balance in Scotland.

Keywords: complex data; data visualisation; zero carbon neighbourhoods; stakeholder involvement.

INTRODUCTION

In recent years, neighborhood-level low-carbon solutions have become a prominent approach to reducing energy consumption and CO2 emissions in the built environment. A review of the literature reveals a variety of terms in this field, including zero energy, low energy, net zero, low carbon, zero emission, and zero carbon communities, neighborhoods, and districts. These terms are often used interchangeably, though they emphasize different aspects, such as energy demand and consumption or emissions related to energy use, leading to variations in data sets and methodologies (See Brozovsky, Gustavsen, & Gaitani, 2021).

Mavrigiannaki et al. (2021) note that the terminology used in these discussions is shaped by definitions, scale, perceptions of spatial boundaries, and the interactions within those boundaries. Brozovsky, Gustavsen, and Gaitani (2021) highlight that urban areas are pivotal for the clean energy transition and for meeting the climate goals set by the Paris Agreement. They emphasize the importance of assessing environmental impact at the neighborhood or district scale as these areas often serve as the foundational units for urban expansion, redevelopment, or transformation by planners and municipalities.

Amaral et al. (2018) define a nearly zero energy district as a part of a city characterized by “a very high energy performance,” where the “nearly zero or very low amount of energy” required is predominantly supplied by renewable sources, including those generated on-site or nearby. Similarly, Norway’s ZEN Research Center describes a zero emission neighborhood as one that aims to reduce both direct and indirect greenhouse gas (GHG) emissions toward net zero over a given period, based on a selected ambition level (Wiik et al., 2022). Koutra et al. (2019) explore the potential of eco-districts to achieve zero energy status, defining a net zero energy district (NZED) as one where energy supply or on-site potential is balanced with final energy demand, and is strategically designed and located to ensure long-term sustainability.

As mentioned by Brozovsky et.al. (2021, p.14) research has primarily concentrated on building-related issues, often overlooking other critical dimensions of a neighborhood, district, or block, such as social and spatial aspects (e.g., microclimate, outdoor thermal comfort). Additionally, factors like location, density, and transportation connections play a significant role in influencing the lifetime emissions of a development, yet these aspects receive comparatively little attention.

To address this gap in the literature the methodology presented in this paper combines buildings energy consumption, mobility of residents, domestic water consumption, household waste, on-site green space maintenance, energy consumption for street lighting, and associated emissions. Moreover, instead of relying solely on data from "low-emission or zero energy pilot projects," the toolkit uses secondary data from existing developments in Scotland built to recent building standards. It provides a methodology for ABC's partner organizations to: 1) estimate lifetime emissions for a site 2) reduce lifetime emissions in existing developments through carbon reduction solutions, 3) select optimal locations for new developments based on lifetime operational emission assessments, and 4) enhance carbon sequestration by improving existing green spaces, validated through scenario testing. The toolkit offers carbon reduction and carbon balance solutions for both new and existing developments, providing a practical methodology for estimating lifetime CO2e emissions for ABC's partner stakeholders, setting it apart from previous models.

Furthermore, this paper extends its focus beyond building operations, such as residential electricity and mains gas consumption, to include community-level activities contributing to CO2e emissions, on site renewables and carbon sequestration. These activities encompass household waste management, residential water consumption, emissions from greenspace maintenance, street lighting, and both public and private transport operations (see Figure 1). The ZCN toolkit, currently applicable to residential developments, defines a neighborhood as encompassing all elements within a site that emit CO2e throughout its lifetime. A zero carbon neighborhood (ZCN) seeks to reduce operational emissions through place-based solutions and to balance or offset the remaining CO2e emissions through on-site renewables and carbon sequestration.

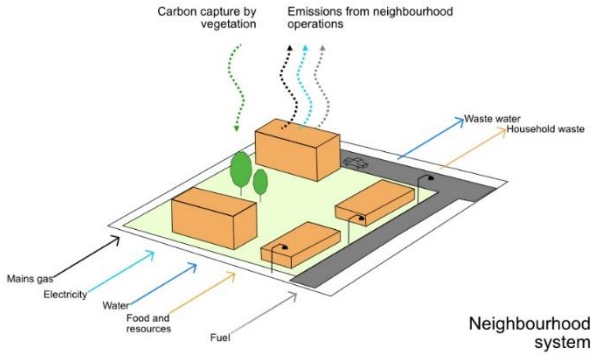

Figure 1: ZCN Neighbourhood system and elements

The presented methodology here is also aligned with the RIBA Plan of Work and the Scottish policy framework, designed to establish key performance indicators (KPIs) for community carbon balance and a series of performance assessment actions to track progress from the early stages of a project. The methodology begins with identifying the relevant legislative framework for place-based carbon reduction. The next step involves selecting appropriate KPIs to assess performance throughout a development's lifetime. Finally, the methodology focuses on generating clear, non-technical outputs from complex data to make the findings accessible to a broader audience.

Our analysis indicates that, despite ambitious net zero targets and policy initiatives such as NPF4, local living guidance, 20-minute neighborhood guidance, the Heat in Buildings Strategy, and Transport Scotland's National Transport Strategy—which collectively aim to reduce operational emissions across various sectors—eliminating CO2e emissions completely from a neighborhood or district is not feasible. However, emissions can be significantly reduced through timely, place-based low-carbon interventions and balanced by on-site energy generation and greenspace carbon sequestration.

Achieving this balance requires careful consideration of several factors, including the location of new developments, transportation links, public transport accessibility, the active travel network within walking distance, land use diversity to support local living, increased on-site greenspace, and the implementation of low-emission technologies for space heating. ABC has been actively working to reduce energy demand in residential units through their own net zero solutions, including the Balance service, which addresses embodied carbon, operational carbon, and community carbon emissions.

In collaboration with the University of Strathclyde, ABC architects propose a methodology for achieving community carbon balance by reducing operational carbon and providing carbon offsetting within a neighborhood's boundaries to balance its lifetime CO2e emissions. To develop this approach, the team first analyzed relevant legislation, regulations, net zero 2045 targets, and best practices for net zero and zero carbon developments in the UK and internationally.

After conducting an in-depth literature review and policy analysis, the team focused on stakeholder analysis, KPI selection, and data identification, verification, and validation. The subsequent sections of this paper detail the steps taken for stakeholder mapping and engagement, data requirements, and the KPI identification cycle.

STAKEHOLDER MAPPING

As a part of toolkit development KTP team has engaged with several local authorities in Scotland. To successful engagement with stakeholders ABC has been collaborated with the Strathclyde Business School (SBS). Through this collaboration the team has worked on stakeholder mapping to identify the target audience that has been identified as the local authorities, community groups, developers and housing providers. Regarding the main stakeholders, the initial case studies were conducted in collaboration with the local authorities in Scotland, as they play a key role in deciding the locations of new developments. The needs/priorities of the stakeholders were evaluated through stakeholder meetings conducted in a semi-structured format. The objective was to comprehend the challenges faced by partner local authorities and their requirements for alignment with toolkit procedures. Through these meetings and ZCN toolkit application to identified case study locations we were able to better understand the priorities and needs of partner organisations, refine the toolkit for site-appraisals and better align with relevant policy framework through embedding it into the toolkit's SOPs and the baseline estimations. Two case studies were conducted with our local authority partners: one focused on a residential development in Edinburgh and the other on two school projects in Renfrewshire. Additionally, a third case study was carried out with a community trust, which has different priorities, targets, and technical knowledge compared to our local authority partners. While not detailed in this paper, the various case studies have been instrumental in testing the toolkit's scalability and adaptability for different project requirements, including residential and public uses.

These engagements with different stakeholders and the presentations of the toolkit outputs have indicated that technical audiences grasp its concepts, the findings and quantitative comparison of different scenarios. However, adjustments are necessary to better align the outputs with the capabilities of non-technical audiences, including community groups. This adaptation involves simplifying the visualization of complex data, using clear visuals and adjusting the terminology to suit the target audience.

Further assessments and stakeholder mapping will be conducted in a subsequent phase to enhance the visualization of complex data for non-technical audiences and refine the toolkit considering the stakeholder needs and priorities.

Following the stakeholder segment analysis a stakeholder need assessment cycle has been developed including the steps below (See **Error! Reference source not found.** for Stakeholder mapping cycle).

1. List the stakeholders / ABC clients: policy makers/ policy implementors / accelerators
   a. Scottish government | Local Authorities | Other public bodies (e.g. SEPA) | Contractors-specialists-architects | Landowners | Community groups
2. identify their role/activities in the planning system: policy makers/ policy implementors / accelerators / service providers
3. identify their goals (e.g. align with the legislation, reduce emissions)
4. segment stakeholders (e.g. primary -local authorities/ secondary-community groups)
5. identify needs / priorities / thresholds / needs
   a. identify focus group
   b. select from: surveys/ questionnaires / workshops / community engagement workshops
   c. data analysis: select data analysis method / analyse information gathered
   d. identify thresholds
6. refine toolkit operations: new information introduced into the toolkit operating procedures (see *Figure 3*)

DATA REQUIREMENTS, VERIFICATION AND VALIDATION:

In collaboration with ABC's partner local authorities, the ZCN methodology has been evaluated using CAD-based implementations and modelling. The toolkit utilizes a mixed-method approach that integrates both quantitative and qualitative methods, such as community surveys on residents' transport habits and secondary data gathering on energy consumption of residential buildings. To ensure the reliability of the emission estimates, the team has validated these estimates by incorporating peer-reviewed methods and tools (e.g., Kelly, Hand, & W., 2023; Centre for Sustainable Energy, 2021).

By incorporating this mechanism, the toolkit ensures that all outputs are consistently reviewed and verified against established benchmarks, thereby improving the credibility and trustworthiness of the results for both technical and non-technical stakeholders. Additionally, the toolkit has been designed to undergo continuous refinement and adaptation, ensuring its reliability and effectiveness in diverse real-world applications. To further strengthen validation, sensitivity analysis has been integrated into the toolkit's procedures, testing it under various hypothetical and real-world scenarios to assess its robustness and adaptability to different conditions See *Figure 2: Project methodology.*

Moreover, real-time energy consumption monitoring will be incorporated in collaboration with partner organizations. However, this addition requires further stakeholder engagement and dedicated funding to fully implement this feature.

Table 1: Data categories and verification/validation procedures

Data category	Verification & validation procedures	
	Stage 1 (current)	**Stage 2 (future)**
Electricity consumption	Post-code level data	Real-time data monitoring
Mains gas consumption	Post-code level data	Real-time data monitoring
Water consumption	Scottish water-benchmark value	Real-time data monitoring
Household waste	SEPA – Local Authority level waste data per household	Real-time data monitoring
Private transport	MOT data, Impact Community Carbon Calculator, ZCN Community Transport Survey, Kelly, et.al. (2023)	
Public transport	Impact Community Carbon Calculator. ZCN Community Transport Survey	
Street lighting	CAD based assessments, Site survey	
Green space maintenance	The housing association / community group / local authority / benchmark values	

For data accuracy on transport related emissions, a community transport survey has been developed and conducted in one of the case studies in collaboration with the relevant community trust. This survey has helped us to validate our initial assessments based on benchmark data and to have more precise estimations on transport related emissions. Additionally, emissions from greenspace maintenance were estimated using on-site turf surface area (in square metre), average annual lawn-mowing frequencies and lawn mower specifications. This information is also validated from the relevant partners for each case study (see Table 1: Data categories and verification/validation procedures).

Three scenarios (Business as Usual, Net Zero 2045 and ZCN Balance) were tested across two case study locations (residential developments – RIBA Stage 7) to compare the lifetime emissions by incorporating various design solutions. The results were shared with local authority partner and the community trust to gather their feedback, refine the toolkit, and understand how different stakeholders interpret our findings. This process also helped us to identify the most effective visuals for communicating the toolkit's outcomes to diverse audiences. Moreover, our interactions with stakeholders revealed differing needs: local authorities require a tool that is practical for site appraisals/option appraisals, while community groups seek to use the toolkit to reduce their lifetime carbon emissions through place-based solutions. Our stakeholder engagements will further take place with additional case studies at different RIBA stages (see ***Figure 3)*** in order to further test and refine the toolkit to extend the toolkits operations from residential sites to other land uses (e.g school projects). This iterative phase will also help with the test of the toolkit applicability and practicality for different land uses.

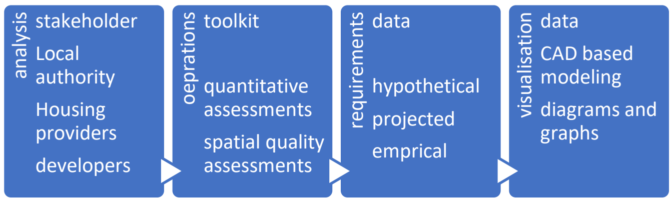

Figure 2: Project methodology

ZCN KPI SELECTION AND ZCN KPI TOOL

The selection methodology for Key Performance Indicators (KPIs) in the Zero Carbon Neighbourhoods (ZCN) project has been designed with a rigorous and context-specific approach, ensuring they effectively capture both building-level and neighborhood-level impacts. The initial step involved listing potential KPIs based on a comprehensive review of existing standards, project needs, and the Scottish policy landscape. This preliminary list was then meticulously evaluated and refined by the project team, considering the specific requirements of the project and the Scottish context.

At this stage, the team closely considered relevant national and regional policies, such as the Heat in Buildings Strategy, National Planning Framework 4 (NPF4), Transport Scotland guidelines, the Local Living and 20-Minute Neighborhood concepts, biodiversity initiatives, carbon sequestration strategies, the Place Standard Tool, and Zero Waste Scotland's principles. By aligning the KPIs with these policies, the team ensured that the selected indicators are not only relevant but also supportive of broader national goals. These KPIs were then embedded into the ZCN toolkit, providing a robust framework for assessing and guiding neighborhood development towards net-zero emissions (See Figure 5 for KPIs selection procedure).

Understanding that a development project undergoes multiple phases throughout its lifecycle, the KPIs were designed to be applicable across all seven phases as defined by the RIBA Plan of Work. This comprehensive coverage ensures that the KPIs are relevant from the initial consultation phase through to the in-use phase, providing a consistent and reliable means of assessment and decision-making at each stage.

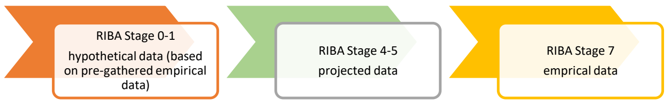

Figure 3: Toolkit operations aligning with RIBA Plan of Work

The ZCN toolkit is composed of two primary components: a neighborhood lifetime emission calculator and a spatial quality assessment tool. The latter is particularly focused on evaluating compliance with national guidelines on local living and 20-minute neighborhoods. The selected KPIs were not only assessed theoretically but also tested through multiple case studies. Using CAD-based assessments, the KPIs were analyzed to determine their effectiveness in operationalizing the ZCN definition and supporting partner organizations in scenario testing and lifetime operational emissions estimation.

This approach allows the team to quantify emissions for various neighborhood configurations, identifying the best options that are closest to achieving a balance between carbon reduction and sequestration over a building's expected 60-year lifetime. The KPIs were validated through these case studies and demonstrated their practical applicability. However, recognizing the dynamic nature of legislation and policy, the KPIs will be periodically reviewed and updated to remain aligned with evolving targets and frameworks.

Initially developed as an MS Excel-based tool, the ZCN toolkit is planned to be further developed into a web-based platform with a user-friendly interface, ensuring broader accessibility and ease of use for stakeholders across different sectors. This transition will enhance the toolkit's functionality, making it a more versatile and powerful resource for achieving zero carbon neighborhoods.

The *Figure 5: KPIS selection procedure* provides a clear, step-by-step outline of the procedure followed in selecting and refining KPIs for the ZCN toolkit, ensuring they are relevant, robust, and practical for achieving carbon balance targets.

RESULTS AND DISCUSSION

This paper outlines the research steps undertaken in the development and application of the Zero Carbon Neighbourhoods (ZCN) toolkit. The methodology successfully identified relevant net zero targets, key stakeholders, clarified their needs, and responsibilities within the ZCN initiative. Through stakeholder analysis, the team engaged with various organizations and conducted case studies to test and refine the toolkit. This helped the team to align the ZCN toolkit with national net-zero targets and stakeholder priorities while adhering to the RIBA Plan of Work, a widely recognized framework that enhances the practicality and reliability of the toolkit across different stages of project implementation. By clearly defining procedures, data requirements, and analysis techniques for each project stage, the toolkit ensures ease of use and adaptability across a range of contexts and project types.

In addition to stakeholder mapping and alignment with the RIBA Plan of Work, a Key Performance Indicators (KPIs) selection cycle was developed to identify relevant ZCN KPIs for each case study. The selected KPIs were then integrated into the toolkit's procedures.

In collaboration with stakeholders several case studies were conducted to iteratively test the proposed methodology. Two case studies focused on existing residential developments (RIBA Stage 7) located in Edinburgh and Perth & Kinross with 40 units and 50 units respectively, where the toolkit's procedures were implemented for relatively small-scale residential sites. Another case study, conducted with Renfrewshire Council, estimated and compared the lifetime carbon emissions of two school projects (RIBA Stage 2 and RIBA Stage 4).

The case studies aimed to test the toolkit's methodology, assess its scalability, identify gaps, and refine the tool for estimating lifetime emissions and conducting scenario testing for carbon reduction. Since the projects were at different RIBA stages, the data sets and sources varied. Smaller site sizes were deliberately chosen to mitigate uncertainties related to data gathering and resource constraints. These constraints, especially in terms of the complexity of larger projects and the intensive resource requirements for data collection and monitoring, limit the current applicability of the toolkit to city-wide implementations.

However, through the case studies, the methodology has been tested and the toolkit has demonstrated its practicality across different project stages and typologies (residential and public). Engagement with local authorities during these implementations has highlighted that embedding iterative carbon estimation and scenario testing in the early stages of project development can significantly support local authorities in complying with net zero targets within their council areas. This approach aids in assessing planning applications and conducting site appraisals, helping to prioritize lower-carbon footprint solutions.

Although the outcomes are not detailed here, the case study applications have provided valuable insights into the feasibility of community-level climate action through estimations of lifetime emissions, scenario testing, place-based carbon reduction solutions, and green space sequestration.

In summary, while the toolkit is currently most effective for smaller sites and individual projects due to resource limitations and data complexities, it has demonstrated potential for future scalability and provides practical approaches for achieving significant carbon reductions at the local level. However, the key risk associated with reaching carbon balance includes the empirical data requirements, strong community and stakeholder collaboration to implement low-carbon solutions, and the financial feasibility of these solutions.

CONCLUSIONS

This paper outlines the research steps undertaken to identify stakeholders, understand their roles and responsibilities, and align the ZCN toolkit with their needs. Due to space limitations, the application of the toolkit through a case study is discussed in a separate paper and falls outside the scope of this one.

Developed through a Knowledge Transfer Partnership (KTP) between ABC and the University of Strathclyde, the project created a practical tool that combines scholarly insight into business pragmatism. In summary, the ZCN toolkit serves as a critical link between academic research and real-world application, offering a robust framework for achieving carbon neutrality in neighbourhoods. Its place-based, data-driven approach ensures that emission reduction strategies are effective and also tailored to the project specifications.

FUTURE WORK

Future work will focus on deepening stakeholder engagement to better analyse and prioritize stakeholder needs, ensuring that the projects align with their goals as well as national net zero targets. This will be complemented by post-occupancy real-time data monitoring to continuously gather relevant data, enhancing the responsiveness and effectiveness of interventions.

Expanding case study typologies in collaboration with local authorities is also among future work which will provide further data and insights into the practical application of toolkit framework. Additionally, engaging with housing associations, developers and community groups will be key in implementing and refining place-based carbon reduction and sequestration solutions, driving sustainable development at the community level.

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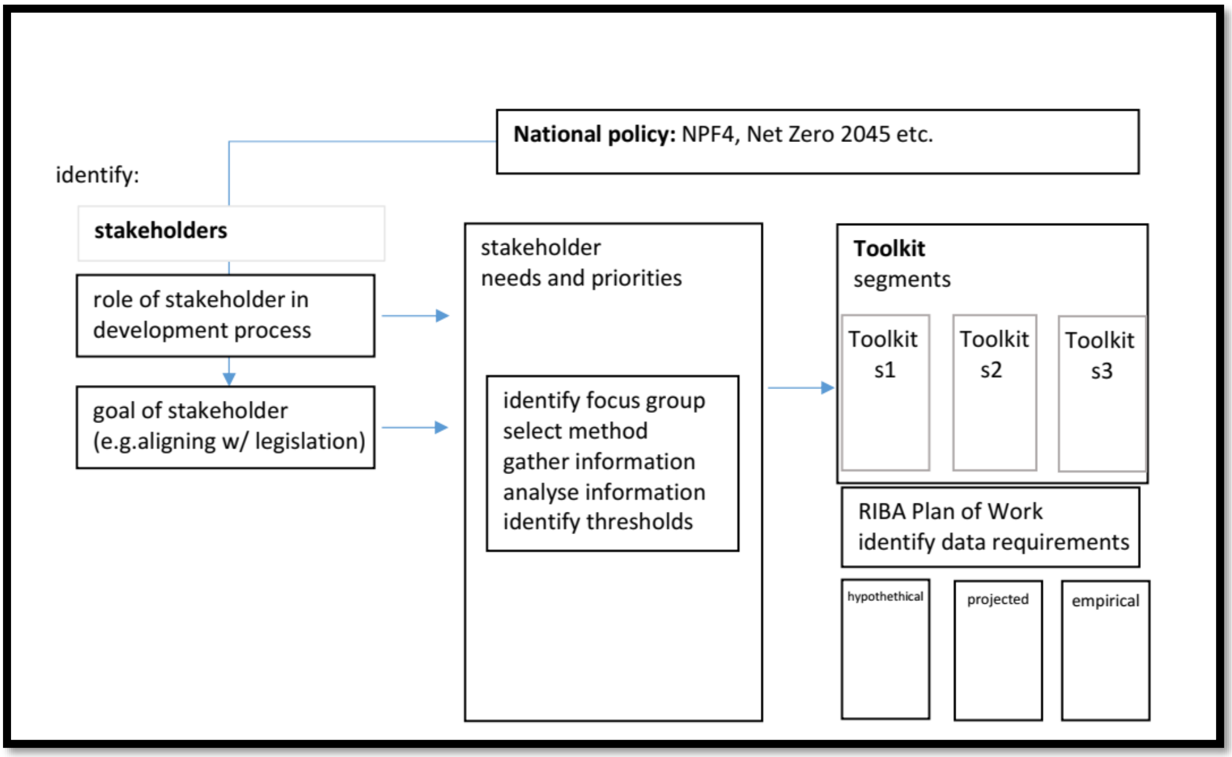

Figure 4: Stakeholder mapping cycle

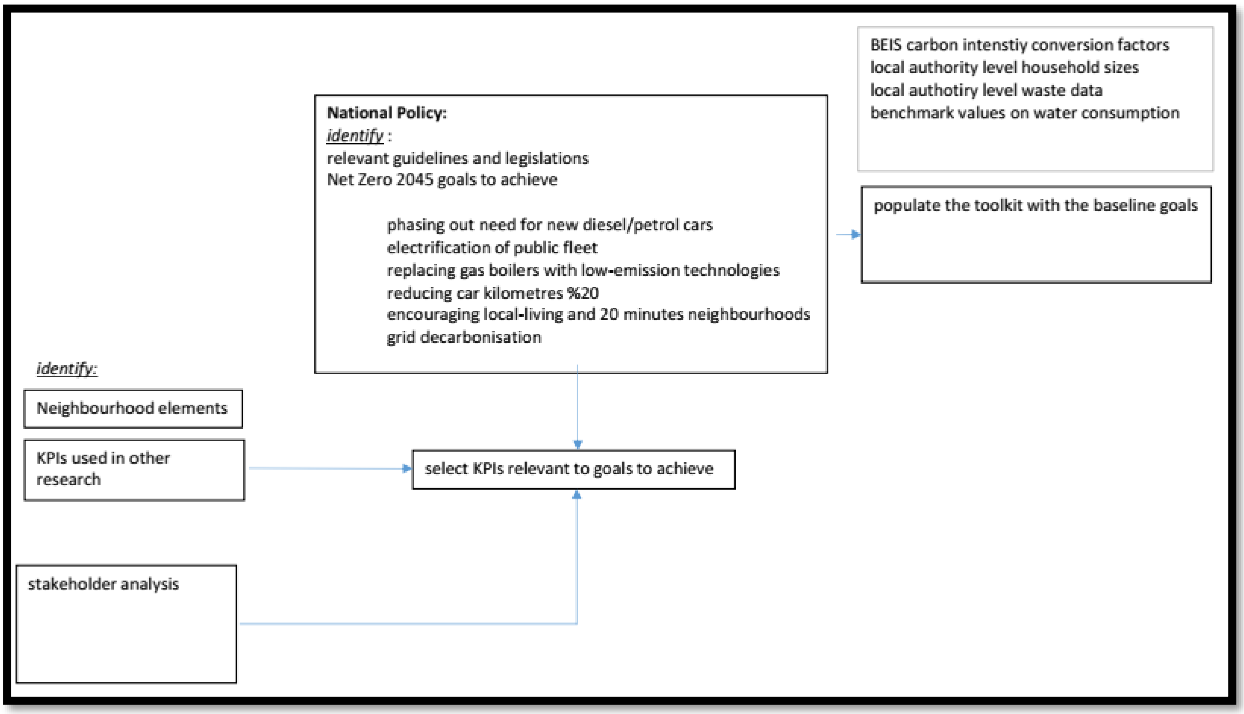

Figure 5: KPIS selection procedure