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Sino-Swiss Cooperation on Zero Emissions Building

Technical Report

Integrated Multi-Energy System Planning

The E-Hub Approach with ZEB-China Demonstration Projects as Case Studies

ENGLISH VERSION

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This report has been produced within the framework Sino-Swiss Zero Emissions Building Project; an international collaboration funded by the Swiss Agency for Development and Cooperation in partnership with the Chinese Ministry of Housing and Urban-Rural Development.

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The Sino-Swiss Zero Emissions Building Project is an international collaboration funded by the Swiss Agency for Development Cooperation in partnership with the Chinese Ministry of Housing and Urban-Rural Development. The project aims to reduce greenhouse gas emissions and enable carbon neural development of the building sector in China by sharing Swiss know-how on sustainable and zero emission building.

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Cover image: ZEB China Demonstration project. Wuxi Fund Park II Construction Project (XDG-2007-Plot 37-Mass C-2) 1# Building (江苏无锡市尚贤湖基金PARK二期建设项目)

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1. INTRODUCTION

1.1. Sino-Swiss ZEB Project

In order to jointly address global climate change and to strengthen cooperation between China and Switzerland in the field of emission reduction in the construction industry, the Ministry of Housing and Urban-Rural Development of the People's Republic of China and the Swiss Federal Ministry of Foreign Affairs signed a Memorandum of Understanding (MoU) on 24th November 2020. The Memorandum is about the development of cooperation in the field of building energy efficiency. Within the framework of this MoU, the Swiss Agency for Development Cooperation (SDC) initiated and funded the Sino-Swiss Zero Emission Building Project. The project aims to support China in formulating the technical standard of zero carbon buildings and long-term roadmaps for reducing carbon emissions in the construction industry. Switzerland contributes by sharing know-how and use cases of zero emission building demonstration projects in different climate zones, while carrying out various forms of capacity building activities, so as to ultimately promote the carbon-neutral development of China's construction industry.

Project Purposes:

- Upgrading existing building energy efficiency standards to Zero Carbon technical Standards
- Implementing demo projects in 4 typical climate zones for testing the new ZEB standards and finding optimization potentials
- ZEB capacity building and knowledge dissemination

Project duration:

- Phase I: 15. Mar. 2021 – 28. Feb. 2025

Project Impact on climate protecting:

- Reduce CO2 Emission in building sector

1.2. Demo projects Wuxi and Dalian

1.2.1. Wuxi Demo project

In March 2022, the Wuxi Demo Project "Wuxi Fund Park II Construction Project (XDG-2007-Plot 37-Mass C-2) 1# Building" was selected as one of the 2nd batch Demonstration Projects of Sino-Swiss ZEB Project. The project commenced in June 2022 and is planned to be completed with its construction in Nov. 2024. The project, situated in Wuxi City, Jiangsu Province, aims to establish a cutting-edge low-carbon industrial park, including a zero-emission conference center, poised to become a new cultural landmark for Wuxi's financial industry. With a total construction area spanning 210,980 square meters, this project seeks to pioneer the region's first low-carbon digital industrial park tailored to its hot summers and cold winters climate. By implementing a range of low-carbon technological measures, it anticipates achieving an annual reduction of approximately 38 kg of CO2 emissions per unit of building area. This underscores its significant potential for carbon reduction, positioning it as a leading international low-carbon digital industrial park.

1.2.2. Dalian Demo project

In March 2022, the Dalian Demo Project "Hutan Donggou Plot Project In Zhongshan District" was selected as one of the 2nd batch Demonstration Projects of Sino-Swiss ZEB Project. The Project, situated in Zhongshan District, Dalian City, encompasses a project construction area of approximately 161,130 square meters. The project's planning and design criteria explicitly stipulate compliance with energy efficiency standards outlined in the national standard GB/T 51350-2019, focusing on "nearly zero-energy buildings." Moreover, the project endeavors to eliminate traditional centralized heating systems. Through the application of innovative green and low-carbon technologies, along with the integration of renewable energy sources, the project aims to significantly reduce energy consumption across various areas, including air conditioning, heating, lighting, elevators, and domestic hot water. This reduction will be achieved while ensuring a high standard of indoor environmental quality, maintaining consistent temperature, humidity, oxygen levels, cleanliness, and tranquility throughout the residential area year-round.

Figure 1 Rendering and Section of the Wuxi demo project in early planning phase. Source: Project Presentation 14.03.2023 ©CABR

Figure 2 Aerial view of Dalian demo project. Source: Project Presentation ©Urban Development Design Group

1.3. Report summary

This report summaries the activities of the "e-Hubs for Chinese ZEB Demonstration Projects (DP)". The selected DPs are located in Wuxi and Dalian. The Wuxi Fund Park II is being developed by Jiangsu Xinhuiheng Engineering Project Consulting Co., Ltd. The Dalian project, the Hutan Donggou plot project, is being developed by Shengding Hutan Binhai Real Estate Co., Ltd.

The aim of the project was to identify energy concepts that would minimize the greenhouse gas emissions of the buildings at both sites while maintaining the business case. This objective was achieved through the use of "multi-energy system optimization", also known as the "e-hub method". Based on this method, the tool provides a consistent evaluation framework for comparing the impact of energy system designs on emission reductions and for identifying optimal energy systems through mathematical optimization. As web-based software, the tool also enabled collaborative development throughout the project and continued access and adaptation of the resulting digital models after the project was completed.

The main outcomes of the project include optimal multi-energy system design alternatives for carbon emission reduction for the DPs in Wuxi and Dalian. Digital models of the energy systems for each demonstration case were developed in collaboration with the stakeholders involved. The digital twin models and optimal system design solutions were disseminated.

The results of both DPs showed that holistic and integrated planning is a key factor for economically efficient emission reduction. Rather than focusing only on investment costs, solutions were quantified and evaluated from a life-cycle cost perspective, which provided valuable insights. For both DPs, optimal system designs were identified that meet the standards of 'low carbon building', 'near zero carbon building' and beyond. These results can be used to guide further feasibility studies of the proposed alternative system designs.

DP Wuxi

DP Wuxi's initial energy system design - prepared prior to the start of the project - already meets low carbon standards. The e-hub methodology was used to evaluate options to further reduce CO2 emissions to achieve the Zero Carbon Standard. These options included increasing thermal energy storage and integrating PV panels on the south, east and west facades. The analysis showed that these measures would also achieve a 28% reduction in life cycle costs compared to the initial system design and 41% reduction in CO2 emissions compared to the first system design.

Further measures have been identified to go beyond the Zero Carbon Standard. These measures include the implementation of full façade PV, the introduction of batteries to increase energy self-consumption, and the extension of the site's internal thermal networks to enable greater coverage of heat demand using the geothermal boreholes. Despite the higher up-front investment required, these measures enable a 13% reduction in life-cycle costs and a 68% reduction in CO2 emissions compared to the first design.

	First Design/ Low Carbon Standard	Zero Carbon Standard	Beyond Zero Carbon Standard
CO2 intensity [kgCO2/m2/yr]	26.9 (28.0)	15.9 (-50% Ref.*)	8.6 (<-50% Ref.*)
Life-cycle cost [million CNY/year]	6	4.3	5.2
Capital Investment [CNY/m2]	283	389	525
Conversion Technologies [MW]	11.7	10.6	10
Rooftop PV [MW]	1.6	1.6	1.6
Facade PV [MW]	-	5.2	7
Batteries [MWh]	-	-	5
Boreholes [MWh]	4279	2597	2987
Thermal Storage [MWh]	0.6	2.3	10
Network [MW]	-	-	2.1

Table 1 Comparison of optimal alternative system designs versus the first design for DP Wuxi. (*Ref: GB55015 General code for energy efficiency and renewable energy application in buildings)

DP Dalian

DP Dalian' s initial energy system design - prepared prior to the start of the project - already meets GB55015 standards, but falls slightly short of Low Carbon standards. The results of the e-hub methodology identify several options to achieve Low Carbon, Near Zero Carbon and Zero Carbon standards.

The Low Carbon Standard is achieved by replacing traditional gas boilers with rooftop Photovoltaic Thermal (PVT) systems, maintaining a similar capital investment while slightly reducing carbon emissions compared to the initial design. To achieve the Near-Zero Carbon Standard, the design has been enhanced to include full coverage of PV panels on the south-west and south-east facades, and the introduction of thermal storage and batteries to further increase energy self-sufficiency. For a further refined Near Zero Carbon Standard, the design includes full façade PV coverage on the south-east, south-west and north-west orientations, and a hundredfold increase in battery capacity to maximize self-consumption.

Alternative measures to achieve the Near Zero Carbon Standard and the Zero Carbon Standard without significantly increasing capital investment in the energy supply systems include the implementation of energy efficiency measures to reduce overall end-use energy demand. However, these options are beyond the scope of this study.

In both DPs, the integration of photovoltaic façade systems on buildings was found to be crucial for economically efficient emission reduction. This technology was initially considered uneconomical by both DP teams. However, through the whole system and life cycle perspective of the e-hub methodology, it became possible to identify façade PV as a favourable solution. The Sympheny algorithms were used to calculate the optimal sizing of the façade PV systems in relation to the sizing of the other installed systems.

Certain limitations of these results should be noted. Although outside the scope of the analysis in this project, it is worth noting that in addition to exploring alternatives in energy systems, energy efficiency measures to reduce energy demand should also be evaluated. Examples of such measures include increasing natural ventilation, using shading and implementing night cooling. In addition, the results need to be considered in the context of certain assumptions underlying the modelling work, in particular the technology investment costs and the definition of operational emissions. In this report, only the amount of emissions reduced by self-consumption, which reduces the need to import electricity from the grid, is taken into account. The export of electricity generated by PV panels is not considered an emission reduction. However, in some definitions, the export of electricity produced by PV panels is considered as an emission offset.

The investment cost assumptions in each DP have been approved by stakeholders. Depending on the implementation stage of each DP, the accuracy of these assumptions may vary. One major difference in the assumptions between the two DPs is the cost of façade PV panels. As façade PV is a key technology for achieving emission reductions, these cost as-

	First Design	Low Carbon Standard	Near Zero Carbon Standard	Zero Carbon Standard
CO2 intensity [kgCO2/m2/yr]	21.9	21.0 (21.0)	15.7 (16.0)	10.2 (-50% Ref.)
Life-cycle cost [million CNY/year]	4.8	4.4	7.1	48.6
Capital Investment [CNY/m2]	147	145	484	4009
Conversion Technologies [MW]	5.5	3.4	3.4	3.6
Rooftop PV [MW]	1.9	1.9	1.9	1.9
Rooftop PVT [MW]	-	0.01	0.01	0.01
Facade PV [MW]	-	-	2	4
Batteries [MWh]	-	0.03	0.4	36.9
Thermal Storage [MWh]	2	3	13	311
Network Pumps [MW]	3.7	3.5	3.5	3.6

Table 2 Comparison of optimal alternative system designs versus the first design for DP Dalian. (*Ref: GB55015 General code for energy efficiency and renewable energy application in buildings)

sumptions should be reviewed before proceeding with the optimal system design alternatives.

Despite these limitations, the stakeholders involved came away from the project better informed about their system design strategies and the associated impact on costs and emissions for their sites. And they better understood the relevance of a whole system, life cycle perspective to energy planning.

Beyond the system designs generated, the process of iteration and refinement itself also served as an important vehicle for knowledge transfer. For both DPs, a series of workshops were held to verify and refine the final models and to finalize the complete results package. This results package included data and interactive digital dashboards providing detailed specifications of the optimal multi-energy system solutions.

In addition, the approach facilitated a more detailed and intuitive understanding of the trade-offs between cost and emissions reduction. This was made possible by the process of systematically testing cost and efficiency assumptions - a process that can be extended to include sensitivity analysis to price changes to identify the key determinants of performance and their relationship to price changes. This can facilitate targeted market research on new technologies.

Overall, it was a successful collaboration with a high level of commitment from all parties. The insights gained into the dynamics of the collaboration provide valuable lessons for future projects, emphasizing the importance of cultural understanding, language preferences and thoughtful use of communication channels in international collaboration.

2. INTRODUCTION TO SYMPHENY AND THE E-HUB METHOD

2.1. Sympheny: introduction and contribution

Sympheny[1] is a spinoff of the Swiss research institute Empa, founded in 2020, with a focus on multi-energy systems modeling and optimization, and experience applying innovative "energy hub (e-hub)" design methods in planning projects in Switzerland and Europe. Sympheny enables a new approach to decision-making in energy systems planning for buildings, neighborhoods, and communities. The basis for this is an innovative, cloud-based software platform that enables holistic planning of energy systems, and the identification of optimally cost- and CO2-efficient energy supply solutions, for any site.

Sympheny is collaborating closely with the intep-Skat team and advising the Chinese planning teams of the selected Demo projects, aiming at decarbonizing their energy supply with maximum effectiveness and cost-efficiency by aiding planners to efficiently assess a large scope of technology options and optimally utilize renewable energy sources and sector coupling opportunities.

This project is a collaboration between the Sympheny team, intep-Skat team, and the Chinese DP teams located in Switzerland and China, referred to as the ZEB project team in this report.

2.2. E-hub method and the Sympheny Web app

At the core of the approach is the use of algorithms to support the identification of innovative energy supply solutions that fit site and customer requirements. It aims to tackle challenges in planning future-proof energy systems, particularly the escalating complexity driven by emerging priorities such as net-zero CO2, energy autarky, positive energy, and negative CO2 in building projects.

Achieving such targets requires maximizing the productive use of on-site renewable energy sources, optimally utilizing synergies and energy cascading possibilities between energy streams and selecting the right combination of energy conversion and storage technologies to temporally balance resource availability and energy demand patterns. Standard energy planning approaches are insufficient to achieve these objectives. Symphony' s software enables the consideration and optimization of multiple energy resources, energy streams, and energy demands – as well as numerous possible technical supply solutions – in an integrated way.

The energy hub model is the backbone of the approach, which have proven effective in identifying optimal designs and control regimes for building, district, and urban energy systems. The models, formulated as mixed-integer linear programs (MILPs), often are solved for the objectives of minimizing total life-cycle costs and life-cycle emissions, offer an advantageous balance of solution efficiency and accuracy [2].

The main equations of the MILP problem are described with (1) load balancing constraints that ensures energy supply matches energy demand at each timestep; (2) capacity constraints that ensure all technologies (e.g., heat pumps, CHP units, batteries) are operated within the defined capacities; and (3) emission or cost constraints that cap the allowable costs or emissions over a time period. In the objective functions, the decision variables are technology capacities and their operation schedules [3].

Building upon this backbone, the web app enables users to specify their project requirements into the MILP formulation, without requiring expertise in mathematical modelling. With its user-friendly interface and detailed graphs presenting results, users enjoy the comprehensive analytics for multi-energy system planning in a consistent, scalable, and efficient manner.

1 "Sympheny." Accessed: Feb. 04, 2024. [Online]. Available: https://www.sympheny.com/

2 L. A. Bollinger and V. Dorer, "The Ehub Modeling Tool: A flexible software package for district energy system optimization," Energy Procedia, vol. 122, pp. 541–546, Sep. 2017, doi: 10.1016/j.egypro.2017.07.402.

3 R. Evins, K. Orehounig, V. Dorer, and J. Carmeliet, "New formulations of the 'energy hub' model to address operational constraints," Energy, vol. 73, no. C, pp. 387–398, 2014.

3. PROCESS & METHODOLOGY

3.1. Project structure

In the course of 6 months, from July to December 2023, the same processes were carried out with both DPs simultaneously. The project unfolded in three phases: it started with digital twin modelling (8 weeks, see Figure 13), followed by analyses and discussions on optimal design alternatives (8 weeks), and concluded with training and knowledge transfer (8 weeks).

The processes in the first two phases are described in a "Four-step approach" in Figure 3. Through weekly online exchange meetings, we engaged stakeholders in all modelling and analysis steps, aiming to familiarize them with the capability of our approach and facilitate constructive collaboration.

In the final phase, we aimed to transfer our approach through multiple online training sessions to the web app, delving into the details of the energy system digital twin and result analyses. Both DPs were provided with complete digital twin models and access to the web app. In October 2023, in-person workshops were conducted with both DPs to reflect on the suitability and scalability of our approach in the Chinese context.

3.2. Four-step approach for planning optimal multi-energy systems

3.2.1. Step 1. Assessment of current situation and identification of objectives

In this step, the initial energy concept, specific boundary conditions, and the relevant matrixes to evaluate the resulting energy systems are exchanged between the ZEB project team.

Depending on the local policies and stakeholder' s resources and priorities, performance targets vary in each project. It is crucial to align the definitions and methods to quantify the performance targets among stakeholders.

Within the framework of the Sino-Swiss Zero Emission Building Project, the main policy framework is the "Technical Standards for Zero Carbon Buildings" [4]. The carbon emission targets for buildings are specified in four standards: low-carbon building, nearly zero-carbon building, zero-carbon building, and whole-process zero-carbon building. These standards are assessed based on the "Building carbon dioxide emission intensity," which is the per-floor-area equivalent carbon dioxide emissions resulting from energy end uses and on-site renewable energy production. The emission accounting method is detailed in section 9.3.

The second target is the total life-cycle cost, which is of interest to the stakeholders to maintain a viable business case. The life-cycle cost considers not only the initial investment in technologies but also factors in replacement costs, the operational and maintenance costs, as well as costs for energy purchase. This indicator reflects the benefits or disadvantages of additional technology investments in the operational phase.

One of the strengths of the approach is quantifying the marginal costs required for emission reduction with the help of mathematical optimization. This way, the DPs can better understand the trade-offs for their energy planning decisions.

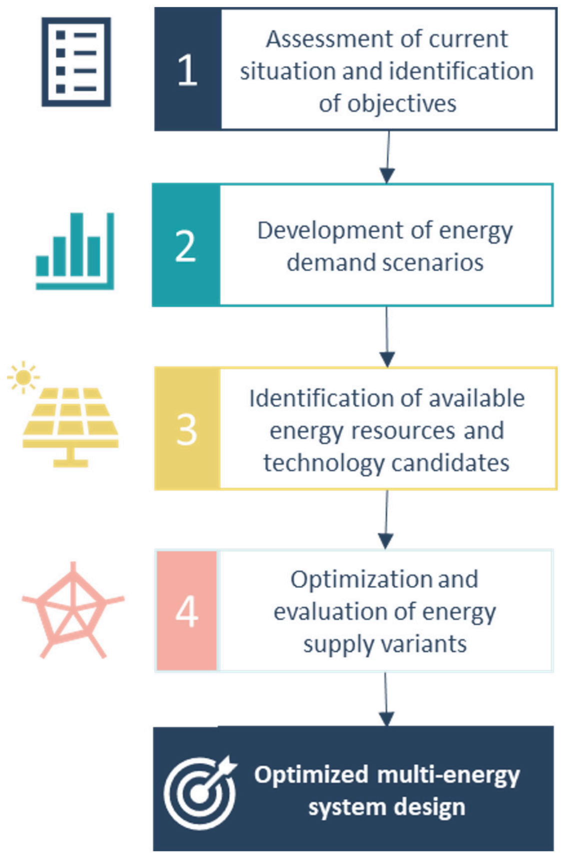

Figure 3 The four-step approach for planning optimal energy systems.

4 "Technical standard of Zero carbon buildings - Exposure Draft." China Architecture & Building Press, Beijing, Jul. 26, 2023.

3.2.2. Step 2. Development of energy demand scenarios

To set up energy demand scenarios, the planned development should be taken into consideration. Relevant energy flows, their characteristics, and potential synergies are identified. Depending on the building use types, typical examples of energy flows are electricity, heating, cooling, and fuels. For both DPs, energy demands are specified with four types of energy flows: electricity, space heating, space cooling, and hot water. The required data resolution for modelling is at hourly intervals over a one-year period. The space heating and cooling demand were acquired through building thermal simulations, provided by both DPs.

For DP Wuxi, the main building uses are commercial (office and complimentary restaurant use type). The ten buildings, with a total of 116 000 m2, on-site are supplied with three energy supply systems, thus the buildings are grouped into three “Energy Hubs” in modelling. The electricity demands from buildings and electric vehicles were extrapolated from weekday and weekend operations into a one-year period, prepared by the ZEB project team.

For DP Dalian, the main building uses are 39 multi-residential buildings and the complimentary schools and retail use types, with a total built area of 161 130 m2. All of the buildings are grouped into one “Energy Hub”, which is connected to another “Energy Hub” which constitutes the energy production center, which produces space heating, space cooling, and hot water that is sent to the building hub.

Hourly energy demand over a year was provided by DP Dalian through building energy simulation.

3.2.3. Step 3. Identification of available energy resources and technology candidates

The goal of this step is to build up a project-specific data repository as inputs for the energy system digital twin models. The data describes the relevant boundary conditions decided together with the stakeholders, which include (a) available energy sources (e.g. solar energy, groundwater, geothermal energy, waste heat); (b) technical and economic parameters for energy production and storage technologies; (c) existing (and planned) infrastructure and grid connections on-site; (d) energy prices.

Working together with the DPs, the ZEB project team compiled relevant data from various sources including the internal databases of respective DPs, and when data is unavailable, the ZEB project team identified suitable local and international databases.

We started by building the baseline model that represents the initial energy system design planned by the respective DPs. In the baseline model, all technology sizes are specified. To explore opportunities in cost and emission reduction, another digital twin model is created based on the baseline model, but with unspecified technology sizes and additional new technologies and energy resources. Table 3 lists the differences between the digital twin models for the “Baseline” and “Expanded option space.” The “Expanded option space” model enables the assessment of a more comprehensive set of possible energy system solutions and the subsequent identification of optimized design solutions.

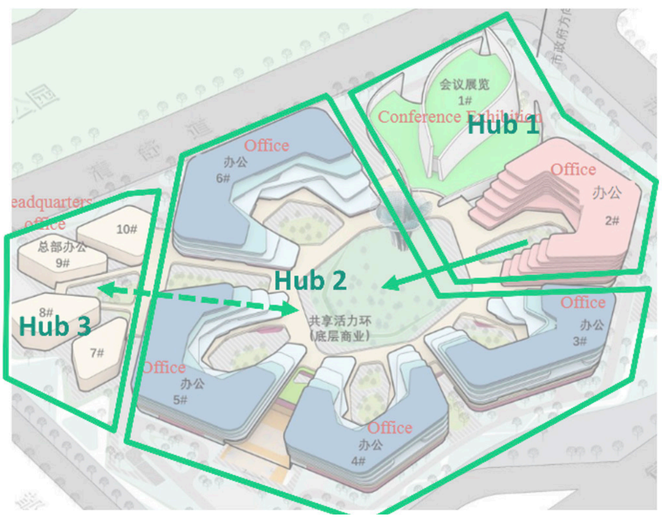

Figure 4 DP Wuxi’s site with ten buildings grouped in three Hubs. The solid arrow between hubs 1 and 2 indicates the internal heating network in the initial project plan. The dotted line between hubs 2 and 3 indicates the consideration of cooling and heating networks. Figure Credit: DP Wuxi (base figure with building footprints)

Model Type	Demand	Energy resources	Energy Market	Technologies
Baseline	as per project plan	as per project plan	as per project plan	as per project plan
Expanded option space	as per project plan	additional resources included as candidates	as per project plan	technology sizes as variables; additional technologies included as candidates

Table 3 Two types of energy system digital twin models ("Baseline" and "Expanded option space"), and the corresponding assumptions.

3.2.4. Step 4. Optimization and evaluation of energy supply variants

After setting up the project-specific data repository, the energy system digital twin is complete and ready for optimization. The outcomes of the optimization are a menu of optimal energy system solutions that minimize life cycle costs and operational emissions. All the solutions are energy system variants yielding the lowest cost for a given emission level.

Each optimal energy system solution specifies the installed capacity of technologies as well as its hourly operation over a year. As a result, all energy flows, including the energy import from and export to the grid, on-site resource utilization, and energy production per technology, energy distribution per network are quantified. The corresponding costs are also detailed in terms of investment, operational and maintenance, energy costs, and income.

This step includes several iterations with the DPs. During workshops, the ZEB project team presented optimal solutions and analyses to guide the DPs to understand the impact factors and identify the need for further model refinement. Refinement involved adjusting cost parameters for technologies, modifying the sizing constraints for technologies or resources, altering technology configurations, etc.

The iteration and refinement process also serves as an important vehicle for knowledge transfer. For both DPs, a series of workshops were carried out, to verify the final models with necessary refinement, and to hand over the complete result package including data and result dashboard providing detailed specifications of the optimal multi-energy system solutions.

4. DP WUXI: RESULTS & ANALYSES

4.1. Energy system digital twin

The main components of the digital twin include the specification of the energy demand, renewable energy resources, and energy system configurations, see Figure 5.

Within the digital twin, the energy system configuration specifies how the energy conversion and storage technologies are interconnected. An example visualization for hub 1 and hub 2 are shown in Figure 6.

Detailed data specifications are logged in the digital twin model on the web app, and the text file is downloaded from the web app.

4.2. Potentials in costs and emissions reduction

We started by exploring and analyzing the impact of individual system design alternatives on cost and emission reduction. The design alternatives range from re-sizing each technology in the planned energy system, the inclusion of new energy conversion and storage technologies, modifying system configurations, and increasing the on-site renewable energy utilization.

Figure 7 presents the various degrees of impact including additional energy storage technologies (green), additional façade PV panels (orange), and additional internal thermal networks (blue) compared to the initial project plan. Favorable solutions are those with lower costs and emissions compared to the initial project plan (dots in the green shade in Figure 7).

Compared to the initial project plan, the highest emission reduction (88%) could be achieved with the inclusion of all additional technologies, but at a significantly higher cost and, therefore, are not considered feasible to implement. On the other hand, several other solutions could achieve around 63% emission reduction at a 25% increase in life-cycle costs. It can be seen that the inclusion of additional thermal storage technology only provides a small impact on emission reduction, while including façade PV demonstrates a strong potential in both emissions and cost reduction.

Benchmarking all the solutions against the “Low carbon building standard” and the “Nearly zero-carbon building standard”, the DP Wuxi project has a strong potential to achieve the “Nearly zero-carbon building standard” and beyond.

Energy Demand 能源需求:
- Space Heating 供暖需求
- Space Cooling 供冷需求
- Domestic Hot Water 生活热水
- Electricity 供电需求
- E-mobility 电动车用电需求

Renewable Energy Resources 可再生能源资源:
- Shallow geothermal 地源热
- Rooftop solar irradiation 屋顶太阳能
- Façade solar irradiation 立面太阳能

Energy Conversion 供能设备:
- Rooftop PV 屋顶光伏板
- Ground-source heat pump 地源热泵
- GSHP (VRV) 地源VRV
- Air-source heat pump 風冷VRV
- Chiller 磁悬浮单冷机
- Façade PV 立面光伏板

Energy Storage 储能设备:
- DHW storage 热水罐
- Boreholes 地井
- Cold water storage 储冷槽
- Hot water storage 储热槽
- Battery 电池

Thermal Network 内部传热管线:
- Hot water network (Hub1&3)
- Space heating network (Hub 2&3)
- Space cooling network (Hub 2&3)

Figure 5 Data specified in the energy system digital twin of DP Wuxi’ s site. The items in black are in both models for “Baseline” and “Expanded option space”, while the items in green are only in the model for “Expanded option space.”

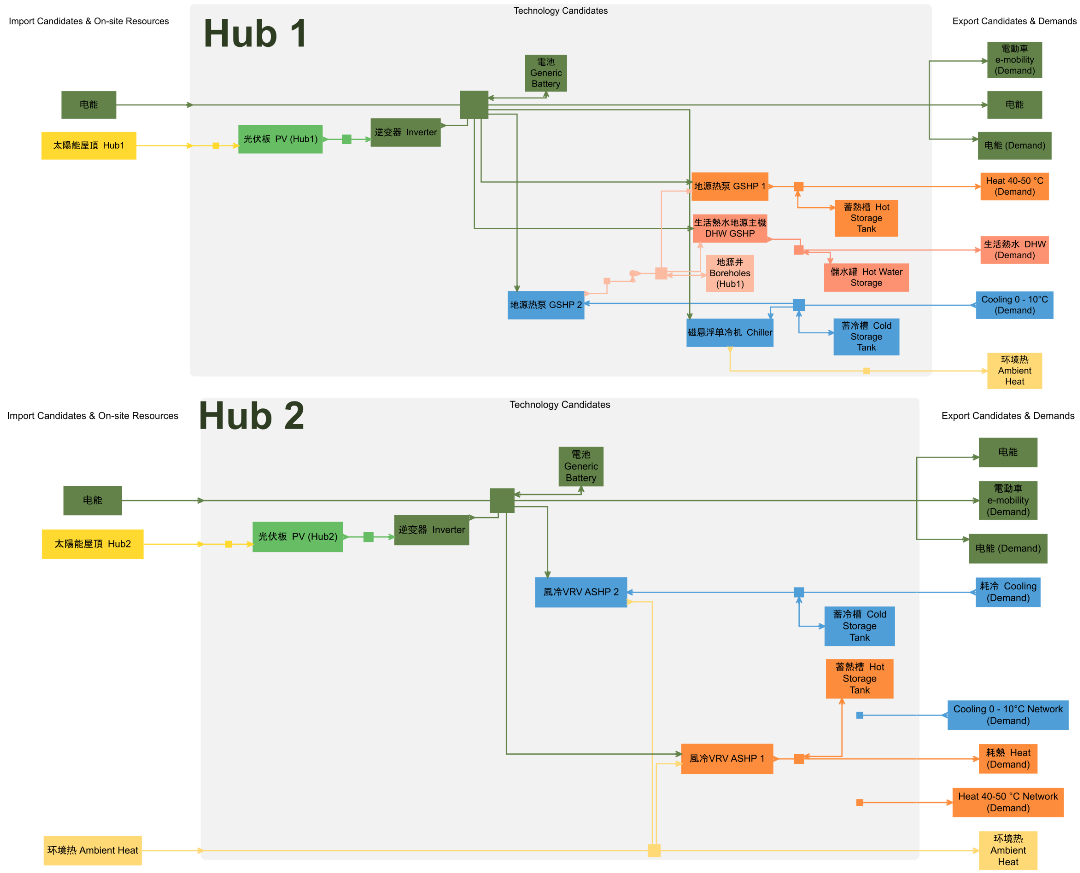

Figure 6 Visualization of the energy system configuration in Hub 1 and Hub2 for the DP Wuxi site. Credit: Sympheny web app.

4.3. Key actions to reduce costs and emissions

Figure 8 shows the life-cycle cost breakdown of the first design (baseline) as well as the optimal system alternatives (solutions A, B, and C in Figure 7). In the system from the first design, the majority of the cost is energy expenses, while in the optimal system alternatives with façade PV (solutions B and C), the energy expenses decrease by around 60%. This is because a portion of the electricity that was initially purchased from the grid is supplied by façade PV. With the increase in upfront technology investment, the operational expenses decreased and thus brought down the overall life-cycle costs.

4.3.1. Energy storage

Introducing energy storage, such as other thermal storage and batteries, contributes to emission reduction by increasing the self-consumption of renewable energy. To achieve the “Nearly zero-carbon standard”, the ideal solution should be similar to the system described by solution B, with the addition of other thermal storages. However, note that the definition of emission offset could impact the emission value ((see section 9.3). Regardless of their contribution to emission reduction, resizing boreholes and other thermal storages can help reduce investment costs on conversion technologies and/or boreholes with optimal sizing.

4.3.2. Façade PV

Façade PV is indispensable for achieving the “Nearly zero-carbon standard” and “Zero Carbon standard.” The south, east, and west façade surfaces are prioritized for PV installation, with the northern surfaces also required to meet the “Zero Carbon standard.”

Even though adding façade PV increases the investment cost by 37% compared to the first design, the overall life-cycle costs are lowered due to the increases in energy sales.

4.3.3. Other energy efficiency measures

Additionally, to meet the “Zero Carbon standard (solution C), implementing thermal networks that supply part of the space heating and cooling from Hub3 to Hub2 reduces both energy consumption and investment in conversion technologies.

4.4. Knowledge transfer and adoption

We have demonstrated that holistic and integrated planning is a crucial enabler for economic emission reduction for the project in Wuxi. The benefits of low-carbon technologies are quantified and evaluated from a life-cycle perspective. This perspective is often less highlighted since the usual practice focuses more on the investment costs.

These results could serve as a guide for further feasibility studies of the proposed alternative system designs. Throughout the series of workshops, we engaged in in-depth discussions on the optimal operation strategies of hot water storage systems and their impact on the overall system. The Wuxi team now comprehends well the interdependencies of technologies on-site as, well as the opportunities for cost and emission reduction that could be unlocked with integrated planning.

These digital twin models not only serve as the inputs for mathematical optimization but also function as comprehensive repositories for all energy-relevant project data. It serves as the basis for further adjustments to analyze the impacts of decisions throughout the project implementation cycle. Furthermore, part of the energy system configuration could be efficiently reused across various development sites.

The DP Wuxi team was convinced of the value of our approach and has since adopted it at another site for project acquisition, with the assistance of the ZEB project team.

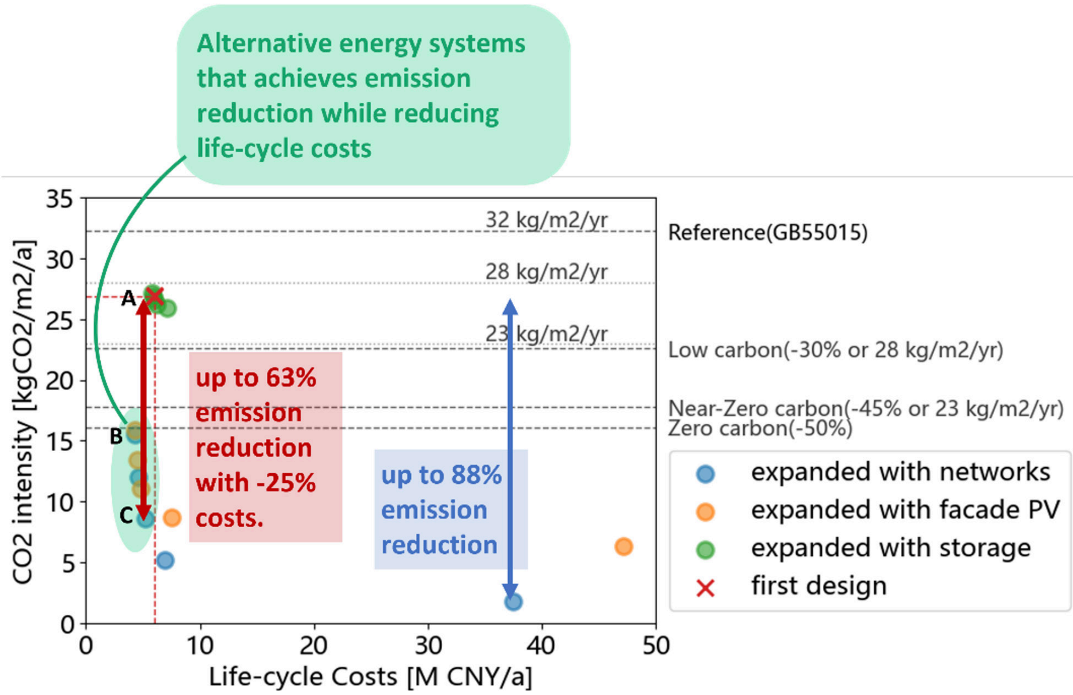

Figure 7 CO2 emission intensities and life-cycle costs of the planned energy system, and the optimal system design alternatives with additional technology options and optimal sizing for the DP Wuxi site.

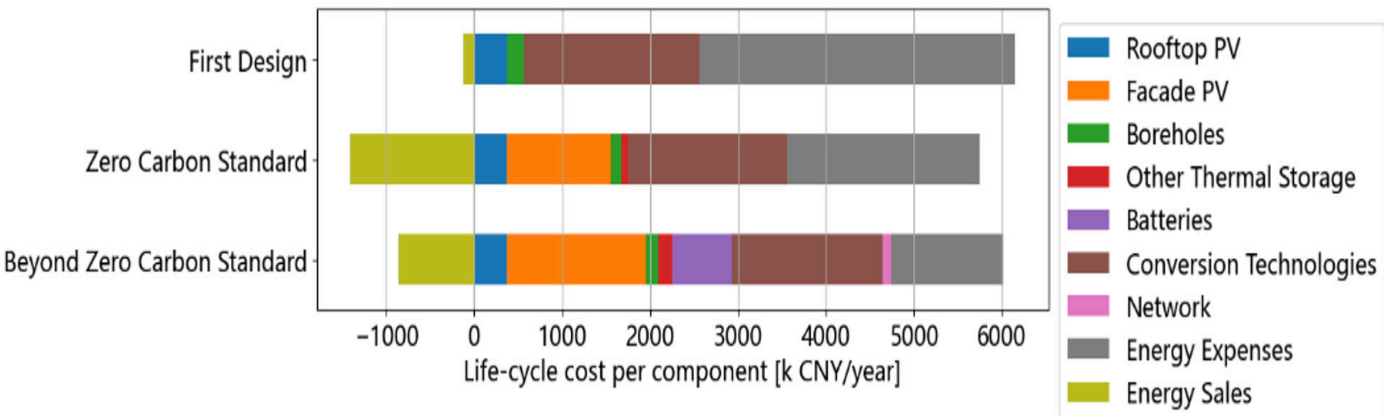

Figure 8 Life-cycle cost per technology group in the first design as well as two other optimal system design alternatives for DP Wuxi' s site.

5. DP DALIAN: RESULTS & ANALYSES

5.1. Energy system digital twin

The main components of the digital twin include the specification of the energy demand, renewable energy resources, and energy technologies, see Figure 9.

Figure 11 presents the energy system configuration of the digital twin model with "Expanded option space," which is expanded based on the baseline system. The baseline energy system uses a centralized sewage heat pump system to supply space heating and cooling demands. The pumping requirement and thermal losses in the distribution networks are specified in the "Pump" technology model. While the hot water demand is supplied by building-level gas boilers. In the expanded system, the available surfaces for façade PV installation are grouped by the surface orientations, and the respective areas and hourly irradiations from each façade group are specified in the model.

Energy Demand 能源需求:
- Electricity 供电需求
- Space Heating 供暖需求
- Space Cooling 供冷需求
- Domestic Hot Water 生活热水

Renewable Energy Resources 可再生能源资源:
- Sewage heat 污水源热
- Rooftop solar irradiation 屋顶太阳能
- Façade solar irradiation 立面太阳能

Energy Conversion 供能设备:
- Sewage heat pump 污水源热泵
- Gas Boiler 燃氣熱水器
- Rooftop PV 屋顶光伏板
- Rooftop PVT 屋顶光伏/热板
- Façade PV 立面光伏板

Energy Storage 储能设备:
- Cold water storage 储冷槽
- Hot water storage 储热槽
- DHW storage 热水罐
- Battery 电池

Figure 9 Data specified in the energy system digital twin of DP Dalian' s site. The items in black are in both models for "Baseline" and "Expanded option space", while the items in green are only in the model for "Expanded option space."

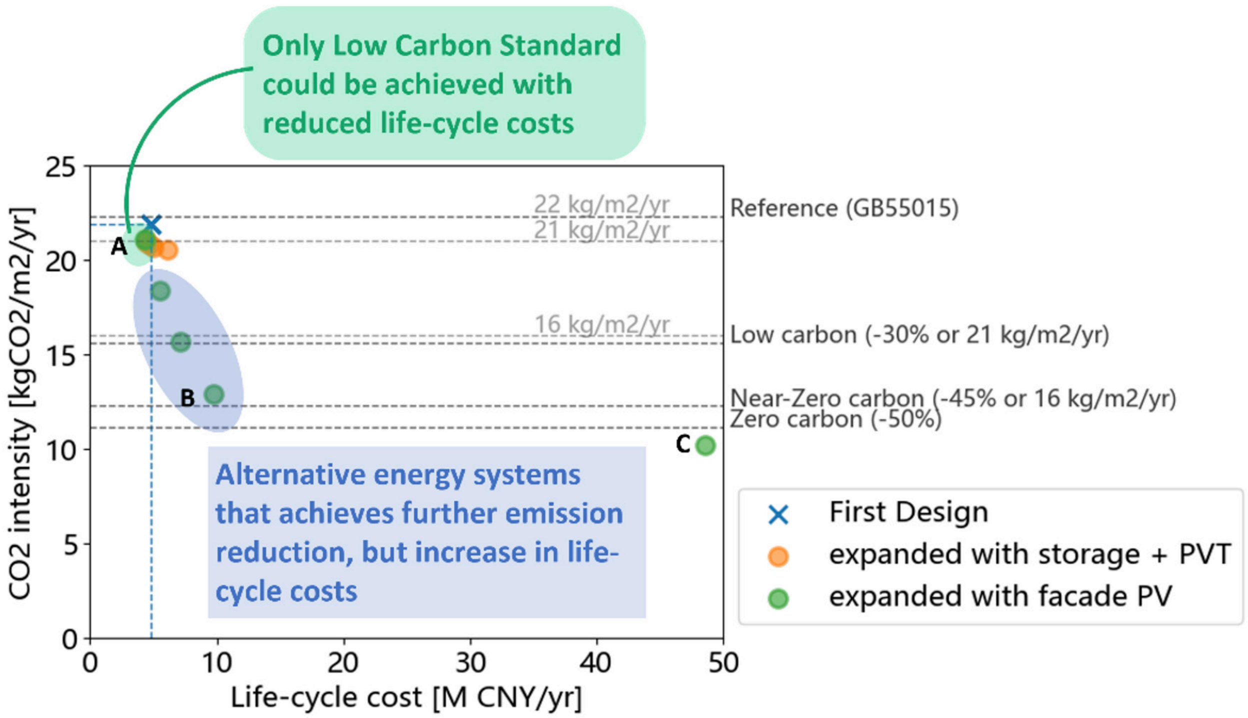

Figure 10 CO2 emission intensities and life-cycle costs of the planned energy system, and the optimal system design alternatives with expanded technology options and optimal sizing for DP Dalian’ s site.

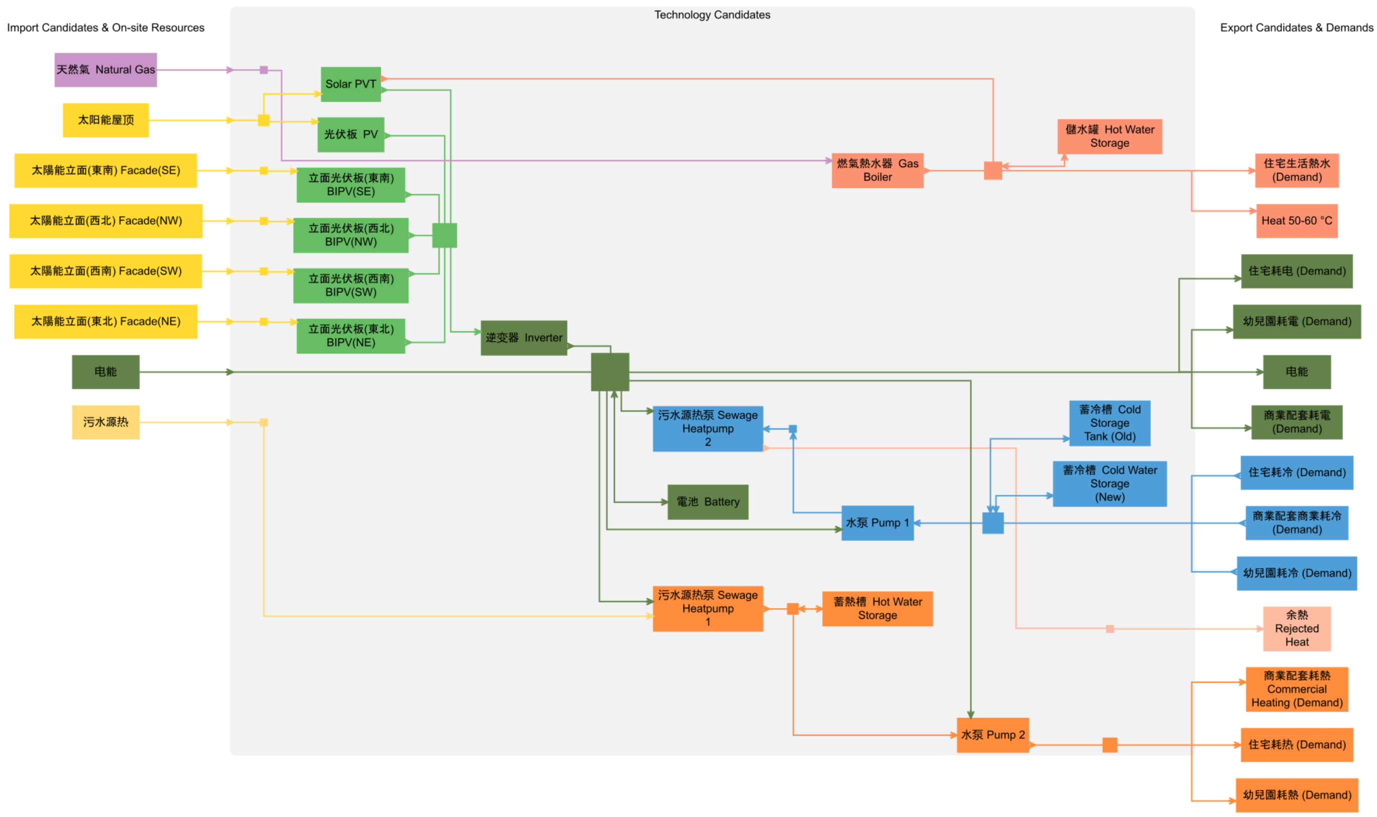

Figure 11 Energy system digital twin with “Expanded option space” for DP Dalian’ s site. Credit: Sympheny web app.

5.2. Potentials in costs and emissions reduction

Based on the first design, the design alternatives range from re-sizing conversion and storage technology in the baseline, the inclusion of new energy conversion and storage technologies, and increasing the on-site renewable energy utilization. Figure 10 presents the various degrees of impact from including additional energy storage technologies (orange), replacing rooftop PV with PVT and including additional façade PV panels (green) compared to the first design. The favorable solutions are those with lower costs and emissions compared to the initial project plan. However, in this case, very few alternative design solutions fall into this category (e.g., solution A), and when they do, the marginal benefits are small.

The solutions with expanded thermal storage technologies only provide a small impact on emission reduction, while including façade PV demonstrates a stronger potential in emission reduction. However, it comes with increases in the overall life-cycle cost (e.g., solution B, C).

Benchmarking all the solutions against the drafted Standards for Zero-carbon Buildings [4] for residential buildings, the initial project plan is 4% and 28% above the low and nearly zero-carbon standards respectively. DP Dalian' s site can easily achieve low-carbon buildings with similar life-cycle costs but would require more than a 46% increase (solution C) in life-cycle costs to reach the Nearly zero-carbon building standard.

5.3. Key actions to reduce costs and emissions

Figure 12 shows the life-cycle cost breakdown of the first design as well as the optimal system alternatives (solutions A, B, C). Solution A achieves Low carbon building standards at comparable costs as in the first design.

5.3.1. Photovoltaic Thermal

The emission saving in solution A mainly comes from replacing the gas boiler with roof PVT (photovoltaic thermal), thus reducing gas consumption. Another portion of the cost savings comes from slightly smaller conversion technologies thanks to the additional heat storage.

5.3.2. Façade PV

Façade PV is crucial to further decrease emissions (solutions B, C) but in higher life-cycle costs compared to the initial project plan. Although the energy expenses decrease by 35-45% with the utilization of façade PV, the investment costs of the façade PV exceed the cost savings. The assumptions for the investment costs of the façade PV significantly impact the overall life-cycle costs. In the assumption made with DP Dalian, the façade PV system costs twice as much per kW as the rooftop PV systems. If assuming that both façade PV and rooftop PV are in a similar price range, it will result in an overall cost reduction for solution B.

For the project site, it is beneficial to install façade PV on the southwest and southeast-facing surfaces.

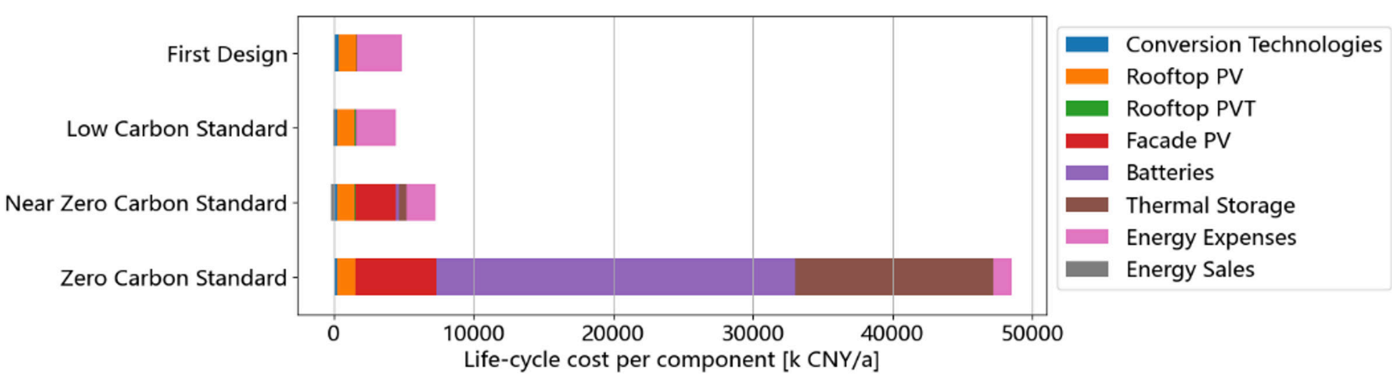

Figure 12 Life-cycle cost per technology group in the initial project plan as well as four other optimal system design alternatives.

In solution B, the southwest and southeast façade surfaces are installed with PV, while in solution C, all available façade surfaces, including north-eastern and north-western orientations, are covered with PV panels. To increase self-consumption and decrease emissions, batteries are being installed. The hourly operation results from project team's optimization show that the batteries primarily store the renewable electricity produced from the south-western façade during noon for later use in the evenings. However, note that the definition of emission offset could impact the emission value (see section 9.2).

5.4. Knowledge transfer and adoption

We have demonstrated the effectiveness of integrated multi-energy planning in identifying effective strategies for emission reduction. This approach can quantify the associated costs at different levels of emission reduction. After understanding the trade-offs in costs and emission reduction, our approach could also facilitate a systematic examination of assumptions related to costs and efficiencies. Using the same modelling framework, the project team could conduct sensitivity analyses on price trends to identify components with high impacts on system performance and determine their ideal price range for economic feasibility. This enables more targeted market research for new technologies.

Considering the temporal dynamics of energy resource availability and demand, the suggested system configurations provide design guidelines that are otherwise not straightforward to analyze. For example, the optimal façade PV distribution for cost and emission reduction does not merely involve maximizing capacity on the surface that receives the highest irradiation.

The DP Dalian team is proficient in building energy modelling and simulation and could swiftly grasp the web app interface. They also recognize the potential for more substantial benefits in more complex projects, such as those involving diverse building use types, multiple hubs, and a broader array of technologies. This acknowledgement highlights the scalability and adaptability of both their expertise and the E-Hub platform, paving the way for impactful applications in complex project scenarios.

6. LESSONS LEARNED

6.1. Integrated multi-energy planning in practice

In this project, we showcased the benefits of integrated energy planning for achieving cost-effective emission reduction in two distinct Chinese development sites. Based on our experience with the two DPs, we found that the available data, although requiring some assumptions, was adequate for delivering convincing system solutions. The following paragraphs summarize the observed standard practices and potential gaps, providing insights into transitioning this approach into common practice.

In terms of technology data and implementation, both DPs possess robust knowledge and experience in common technologies. They are also strong in implementing certain key low-carbon technologies, such as boreholes, ground-source heat pumps, and sewage heat pumps. Although the analysis highlights the strong emission reduction potential of façade PV systems, both DPs express less interest due to a lack of practical experience. Despite cost competitiveness, additional efforts are needed to provide comprehensive market research and best-case examples to encourage further exploration of the feasibility of this technology.

In terms of data regarding energy demand and resources, both DPs are familiar with these datasets, although they primarily use less detailed information (mostly annual aggregation). However, for multi-energy planning, having temporally resolved data is crucial for optimizing the sizing of renewable and storage technologies. Improved real operational knowledge could enhance the analyses for both DP sites by refining certain assumptions. For example, there might be overestimation in cooling energy demand, and the seasonal variations in sewage temperatures are unknown. When time allows, this gap could be partially addressed with sensitivity analyses and scenario analyses.

The standard practices are already facilitated with similar datasets for multi-energy planning, but the integrated approach to systematically combine the data in the same level of detail has yet to be adopted. Achieving a comprehensive district perspective and considering all types of constraints simultaneously are the crucial steps to respond to enhanced emission regulations that may not have been economically achieved without integrated planning approaches. Therefore, it is imperative to transform standard practices to adopt this integrated approach to ensure more effective handling of complex multi-energy systems.

6.2. Influence of policy on energy planning

In line with China' s dual carbon targets, it is anticipated that more energy-related policies will be introduced in the building sector. The policy framework could directly impact the planning decisions for energy systems. Example of such policies include implementing building code, carbon tax, emission certificates, subsidies, incentives, renewable energy targets, renumeration mechanisms, framework for local community ownership of renewables, energy market reform etc.[5].

The policy reference for this project is the "Technical Standard for Zero Carbon Buildings." It is anticipated that this building code will be mandated for future buildings and districts. One of the indicators outlined in this standard is the "Building carbon dioxide emission intensity," defined in equation 2 (see section 9.2). Notably, this equation considers renewable energy export to grids as emission reduction. This method incentivizes maximizing onsite renewable energy production, and requires sufficient grid capacity for grid feed-in.

On the contrary, this report follows equation 1, where renewable energy export is not considered as emission reduction. This approach promotes self-consumption and requires an adequate amount of energy storage to balance the mismatch between energy production and consumption.

Policy makers should conduct regional scale analyses on grid capacity and the associated grid expansion costs under various policy scenarios. These analyses will help comprehend which policies could achieve maximum impact (e.g., emission reduction) while ensuring appropriate cost allocation and technical feasibility. Other policies and market mechanisms mentioned above are not yet clearly specified for the Chinese context. Given the lifespan of energy systems often more than 20 years, it would be beneficial to understand what could be anticipated. A well-defined policy roadmap for the next 20 years could assist the building sector in effectively aligning with rapid carbon reduction targets and avoiding lock-in effects.

5 "20 Renewable Energy Policy Recommendations," International Energy Agency. Accessed: Feb. 05, 2024. [Online]. Available: www.eu4energy.iea.org

6.3. Feasibility of virtual international collaboration

This project is a collaboration between the Sympheny team, ZEB China team, and the Chinese DP teams located in Switzerland and China. The collaboration was mostly completed via online exchanges. A physical meeting was held in October 2023 for result discussion and training workshops. Overall, it was a successful collaboration with great level of engagement from all parties.

Weekly online exchange schedules were established between the ZEB project team and the Chinese DP teams in the beginning of the project, proving to be an effective format for ensuring progress. During the weekly exchanges, the ZEB project team introduced specific topics related data collection and their potential impact on results, achieving a dual purpose. Firstly, it aids DP teams in efficiently collecting data with a clear understanding. Secondly, it facilitates knowledge transfer on the aspects such as the impact on energy system performance, methodologies, alternative data resources, and international building standards. While this exchange format is effective for step 1-3, and step 4 could be enhanced with in-person training at the very beginning of the project.

Certain exchanges are more effective if carried out in-person. The workshop held in Beijing in October 2023 with all DP teams was effective. It was a meeting with over 20 participants engaged in discussions that might not have been as dynamic in an online setting. To enhance the adoption of the web-app, an initial one-day, in-person workshop could have been beneficial. Such an approach might have facilitated subsequent online exchanges during result analysis and model iterations (step 4).

The primary language of collaboration between the ZEB project team and the Chinese DP teams was Mandarin. Although the Chinese DP teams have a basic proficiency in English, the project could not have been as efficient and effective if carried out in English. Most members in the DP teams prefer and are more open to communicate in Mandarin. Relationship building is also crucial for establishing trust and fostering an open environment for exchange. This includes the use of WeChat as means of communication. It is observed that the DPs are more willing to provide feedback and clarify questions promptly via WeChat compared to email exchanges.

All the above factors were crucial for the successful and timely completion of the project. Building a strong collaborative environment through structured exchange formats, language preference considerations are particularly vital. These insights into the dynamics of collaboration of this project offer valuable lessons for future projects, emphasizing the significance of cultural understanding, language preferences, and the thoughtful use of communication channels in international collaboration.

7. OPEN QUESTIONS

When interpreting the results and incorporating them into further decision-making, several open questions should be considered. The most important points are the cost assumptions on façade PV panels, the assumptions on end-use energy demand, and the definition for operational emissions.

These assumptions have been approved by the respective DPs at the time of the project, with the best knowledge available depending on the implementation stages of the respective DP. The projects and analysis are designed in a reusable manner, allowing for future iterations to update assumptions easily.

7.1. Cost assumptions for façade PV panels

The investment cost assumptions in each DP have been approved by the stakeholders, but the accuracy of these assumptions may vary depending on the implementation stage of each DP. One major difference in the assumptions between the two DPs is the cost of façade PV panels. As façade PV is a key technology for achieving emission reductions, these cost assumptions should be reviewed before proceeding with the optimal system design alternatives. At the time of the project, both the Dalian and Wuxi DPs had no experience of implementing façade PV and no accurate price data.

Therefore, the cost assumption for façade PV is supported by this analysis [6] [7], which summarises the implementation experience in Switzerland. The general trend of the cost assumption for BIPV suggests that the façade PV could replace the traditional cladding and substructure, and therefore should be subtracted from the total cost of the façade PV system for a fair comparison.

Based on this information, DP Wuxi agreed to align the cost of façade PV with the current cost of rooftop PV, while DP Dalian, taking a more conservative approach, decided to set the cost at twice that of rooftop PV. As a next step, we suggest gathering information from implementation data in China.

7.2. Assumptions on end-use energy demand

The end-use energy demand data for buildings were provided by the respective DPs via energy simulation. During the previous exchange, some Swiss experts suggested that the end-use demand for space cooling is on the higher end. This requires further adjustment of the expected use patterns in terms of setpoint temperatures, operating hours and ventilation preferences. In China, according to the DPs, the function of air conditioning goes beyond providing thermal comfort, it also plays a crucial role in providing air filtration to ensure indoor air quality.

Although outside the scope of the analysis in this project, it is worth noting that in addition to exploring alternatives in energy systems, energy efficiency measures should be evaluated to reduce energy demand. Examples of such measures include increasing natural ventilation, using shading and implementing night cooling.

7.3. Definition for operational emissions

The method used to calculate operational emissions impacts the energy system design and operational strategies of the sites. According to the draft of “Technical standard of Zero carbon buildings” [4], carbon emission offsets could be achieved by exporting renewable electricity produced on-site to the grid (see equation 2 in section 9.3). In this case, it does not incentivize the self-consumption of on-site produced renewable electricity.

In this report, emission reduction is accounted for only the number of emissions reduced through self-consumption (see equation 1 in section 9.3), which decreases the import of electricity from the grid. Exporting electricity produced from PV panels is not considered as emission reduction. This calculation method quantifies the impact of the emission reduction of the project site. Both accounting methods could be implemented in this model, however, due to time constraint, both DPs agreed on using this accounting method.

Typical impacts on system design between these two accounting methods include the sizing of renewable technologies (e.g., PV panels) and energy storage technologies (e.g., batteries, hot water tanks, cold water tanks).

6 SolAR, “THE COSTS OF BIPV,” Solarchitecture. Accessed: Aug. 28, 2023. [Online]. Available: https://solarchitecture.ch/the-costs-of-bipv/

7 Joint Activity Scenarios and Modelling (JASM), “Decentralized energy conversion technologies.” 2020. [Online]. Available: https://data.sccer-jasm.ch/energy-conversion-decentralized_technologies

Further comparative analysis on optimal system behavior under these two accounting methods could be valuable for policymakers. Such analysis can help set performance targets and the corresponding accounting methods that encourage adoption of renewable technologies while avoiding negative side effects, such as grid congestion.

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