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Energy Systems Language: An analytical tool for studying the climate adaptation of buildings

Simin Tao and Qi Zhang

Since the last century, humans have begun using coal, oil, and other stored energy sources to supplement solar energy, while pollutants from fossil fuels pose risks to the local and global environment. As more architects and scholars focus on today's climate and energy issues, numerous environmental simulation tools and standards have been developed. Some studies prioritise mechanical systems over building design and limit buildings to standardised rating systems. Therefore, it is necessary to establish a comprehensive contextual system, taking climate, architectural aesthetics, technology, and other relevant factors into account.

From a thermodynamic perspective, the building is an open system, constantly exchanging energy with its environment. Building design can play a crucial role in organising the energy flow within the environmental system, and an optimised building climatic design can effectively maximise the amount of energy available from the environment. This paper employs the energy systems language as a tool to analyse the climate adaption of buildings and to evaluate their climate strategies through a unified dimensional energy flow. It enables an objective analysis of climate, energy, building form, and human bodies within an integrated system. Additionally, the paper applies the energy systems language diagram to three case studies, including the study of a vernacular house, the design process of an infrastructure building, and the post-occupancy evaluation (POE) of a student centre building. By doing so, this study provides different scenarios that utilise energy systems language to analyse the relationship between climate, energy and form.

KEYWORDS: energy systems language, climate adaption, climatic design, thermodynamic architecture.

RSD TOPIC(S): Architecture & Planning, Mapping & Modelling

Buildings as an open thermodynamic system

A thermodynamic system refers to a finite macroscopic region that is studied within the field of thermodynamics. The system is defined by its boundary, which separates its interior from the external environment. Through this boundary, the system is capable of transferring different forms of energy to the environment. From a thermodynamic perspective, a building can be regarded as a thermodynamic dissipative structure similar to living bodies. The climate serves as the external environment of the building system, while the building envelope acts as its boundary (Abalos & Sentkiewicz, 2015). In order to avoid reaching thermodynamic equilibrium, buildings continuously exchange energy and matter with the environment. The functioning of this dissipative structure is closely linked to its internal organisation. Consequently, the architectural forms can be utilised to regulate energy flows within their respective systems. A well-designed building envelope can effectively maximise the utilisation of available energy from the climate, and a well-planned building program can facilitate the rapid transfer of energy and the generation of new energy types (Kong et al., 2018).

Energy systems language in buildings

Context of climate, environment, and architecture

Energy systems language, also known as Energese, was initially proposed by Howard T. Odum, an American ecologist renowned for his ground-breaking work in ecosystem ecology, in the 1950s. Odum's contributions extended beyond his research in general to systems theory, as he also put forth innovative concepts related to additional laws of thermodynamics. Energy systems language emerged as an abstract diagram within systems ecology to illustrate the flow of energy. The language employs specific symbols to represent the roles of producer, consumer and energy storage within a system. It utilises the concept of *emergy* to unify the dimensions of energy flow, providing a clear depiction of the internal structure of complex systems and offering visual insights into their organisation. In his book *Environment, Power, and Society for the Twenty-First Century*, Odum (1971) expanded the scope of energy study to encompass a broader field. He positioned thermodynamics as a scientific tool for understanding and explaining the social environment. Odum's idea of systematic self-organisation aligns with the perspective on climate adaptation within the field of architecture.

Braham's (2015) views in "Architecture and Systems Ecology" aim to introduce energy systems language as an analytical tool in the field of architecture. By employing this language, a comprehensive context can be established to evaluate the climate adaptability of buildings. This evaluation encompasses various aspects, including energy use for construction materials and even architectural style (Figure 1). Furthermore, energy systems language enables an objective assessment of the energy exchange between the environment and buildings. It sheds light on the dynamic characteristics of buildings in relation to climate adaptation, offering a deeper understanding of their behaviour in response to changing environmental conditions.

Units and compositions

Within a thermodynamic system, there exist various small-scale energy transformations that form the basis of energy systems language (Figure 2). By utilising these units, energy systems language provides a visual representation of the energy dynamics within a system and facilitates the understanding of energy flows and interactions in architectural contexts.

Units of energy systems language

Energy Flow: The fundamental unit of energy systems language represents the circulation of energy or matter within a system. It is depicted as a line with an arrow indicating the direction of flow.

Energy Loss: This symbol represents the dissipation of low-grade energy from the system that cannot be further utilised. It is typically positioned below the system frame in the diagram.

Subsystem Frame: The dashed rectangular box indicates the boundaries of a specific *subsystem* within the diagram. The subsystem is defined based on the research objectives and may encompass the internal and external interfaces of a room, facilities, and human activities, for instance.

Source: The symbol of source simplifies various complex production processes. Any input entering the boundary is considered a source. Renewable resources, such as sunlight, wind, and rain, are commonly depicted on the left side of the boundary.

Consumer: This unit is responsible for storing and transducing energy while providing feedback to enhance energy inflow. For example, human is the most common consumer. The symbol is typically located on the right side of an energy systems language diagram.

Interaction: This unit signifies the interaction of energy flows, which can result in the output of one or more energy flows. It often represents a process of improving energy quality.

Producer: Producers collect, transduce, and transfer low-grade energy to the system. They indicate internal storage and interaction behaviours. Typical examples of producers are plants.

Storage Tank: This symbol denotes entities capable of capturing and storing energy, releasing it according to a predefined pattern. It helps balance the inflow and outflow of energy.

General Process: This unit simplifies a complex subsystem into a general process to enhance the comprehensibility of the diagram. It may represent a spatial unit, such as a kitchen, that functions in energy conversion and storage.

Switch: The symbol represents optional human activities within architecture, including intelligent control of variable components, etc.

Three scales

Markus et al. (1980) propose that a system model can be established by considering the thermodynamic relationship between climate, buildings, and the human body. A building system relies on its external climate system while providing protection and energy to the internal human body system. In a similar vein, energy systems language can be categorised into three scales (Figure 3):

1. Energy Capture
2. Energy Programming
3. Energy Regulation

Each scale represents a subsystem layer. The first layer, *energy capture*, pertains to the building envelope's ability to harness external climate energy. The second layer, *energy programming*, is enclosed by an envelope and focuses on the energy balance of functions within the building. The third layer, *energy regulation*, involves environmental control components integrated into the form and space of the building (Tao, 2020).

These three scales imply a hierarchy structure within the thermodynamic system of architecture, encompassing the site, envelope, structure, tectonics, interior, and additional facilities. Through continuous interaction and coupling, if the mechanism governing these scales can be clarified, it would facilitate the analysis of a building's energy response to climate. For instance, with changes in microclimate, the dynamic response of the building envelope can be utilised to regulate energy flow. Energy systems language provides a means to analyse the dynamic characteristics of a building envelope functioning as a climate filter.

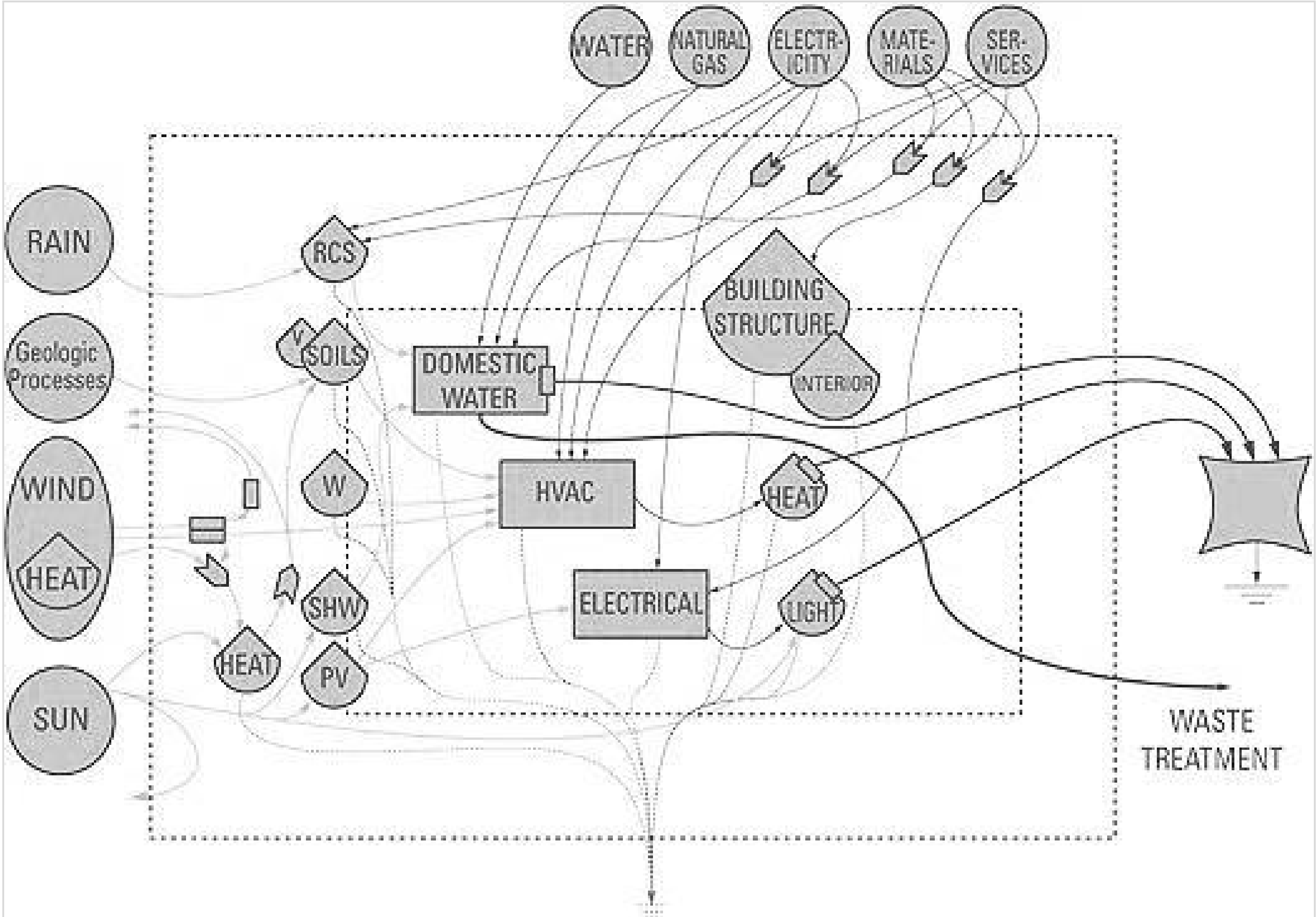

Figure 1: Energy systems language of a building. Source: Srinivasan & Moe, 2015.

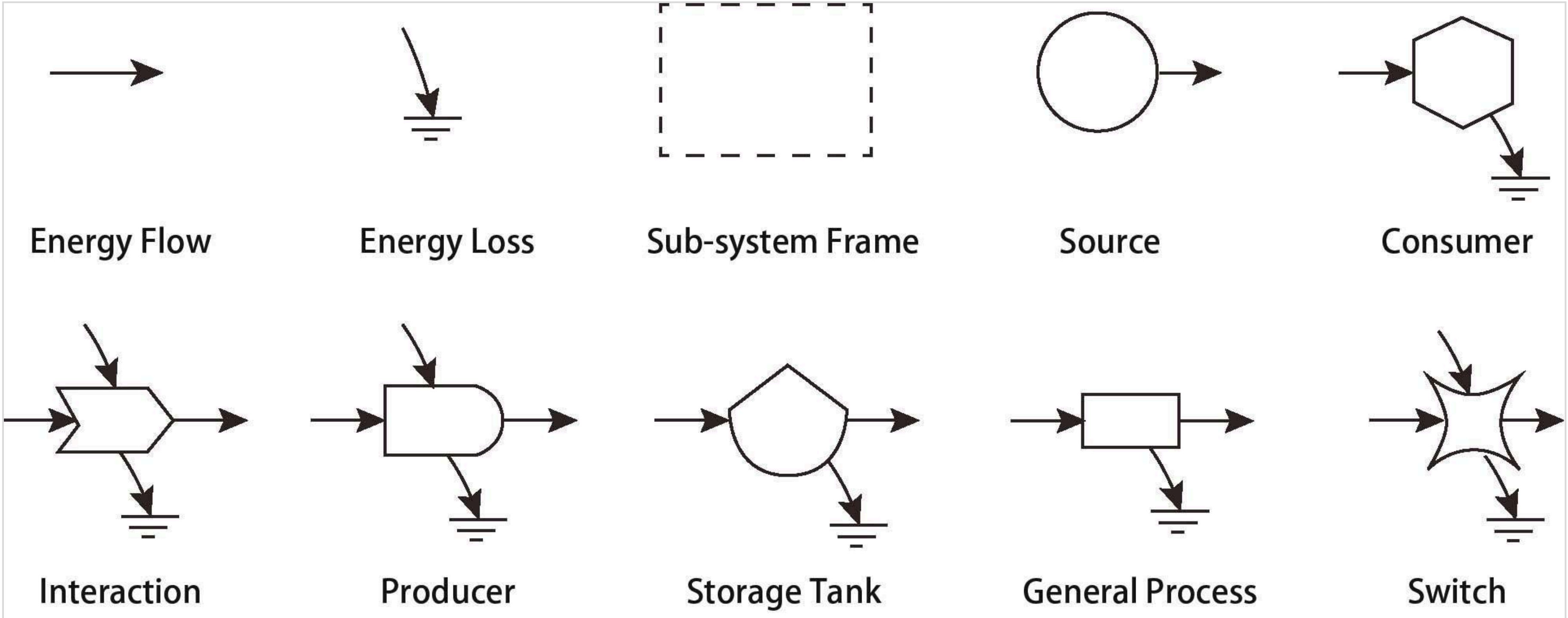

Figure 2: Units of energy systems language. Source: Simin Tao.

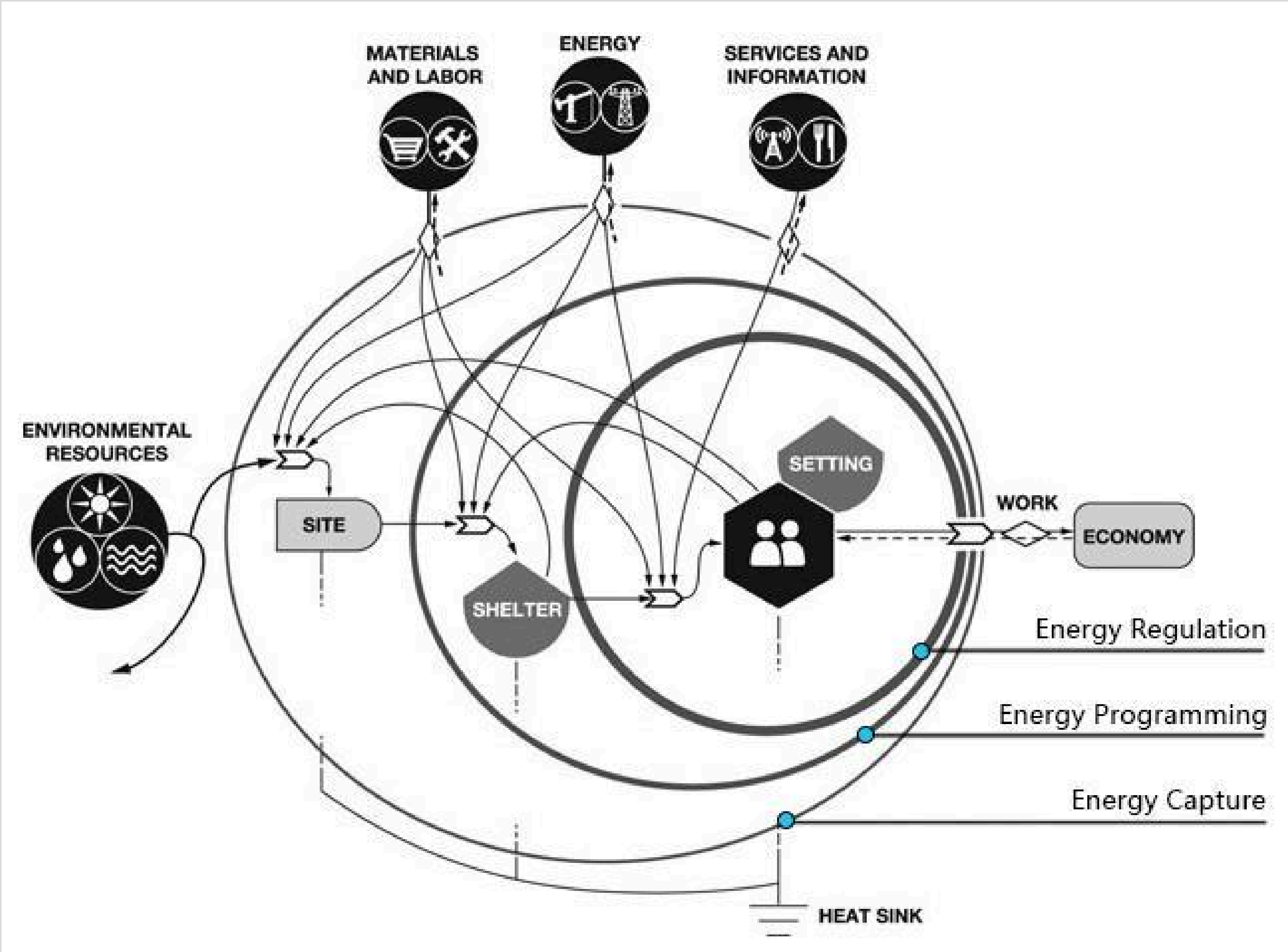

Figure 3: Three scales of energy systems language (Source: Braham, 2017).

Case studies

Three application scenarios of energy systems language

Energy systems language proves to be a versatile tool applicable in various scenarios, including study, design, and analysis. 1) For study: it can be employed to examine the climate adaptation of specific vernacular houses. 2) For design: it can serve as an assistant in the climatic design of contemporary buildings. 3) For analysis: it can function as an indicator in post occupancy evaluation (POE) to assess the environmental performance of constructed buildings. This paper presents three case studies conducted in China, demonstrating the application of energy systems language in these three scenarios. The language is utilised to describe the structure of their thermodynamic system and to elucidate their energy response to the climate.

1—For studying the climate adaptation of a vernacular house

The Dacuo settlement in Hushan is an ancient town that exemplifies the red brick culture of Quanzhou, China. Quanzhou experiences a subtropical marine monsoon climate characterised by warm and humid conditions, sufficient sunshine, and heavy rainfall. Vernacular houses in this region primarily address the challenges of summer heat and humidity. Based on the analysis using energy systems language, the major climatic strategies employed in Dacuo include (Figure 4):

Settlement Patterns: The Hushan Dacuo settlement is designed as an inward enclosure around the ancestral temple, with branch-like alleys distributed among the densely constructed houses. These alleys are mostly shaded by the wall and eaves. The presence of small squares, narrow lanes, and terraces at varying scales creates a stack-ventilation effect through the differential solar radiation. The density of outdoor space enhances the wind pressure ventilation.

Horizontal Layout: Hushan Dacuo follows a symmetrical arrangement with courtyards that are narrow and open. The colonnades are positioned between rooms, forming “cold alleys”. The courtyards serve as air outlets, promoting organised ventilation. The compact layout and thick exterior walls prevent excessive heat gain during summer and infiltration of cold air during winter.

Vertical Layout: The roof timber frame is covered with two layers of tiles, and the narrow interlayer of tiles acts as insulation. The dovetail ridge is lower in the middle and higher at both ends, facilitating the efficient discharge of rainwater away from the wall. The design of the house allows for the control of sunlight by adjusting the depth of the eaves.

Envelope Characteristics: The interior walls in Dacuo predominantly utilise lightweight wood, and the wall grilles can be opened or closed to regulate ventilation. On the other hand, exterior walls are thick and thermally stable, typically constructed using masonry or rammed earth techniques.

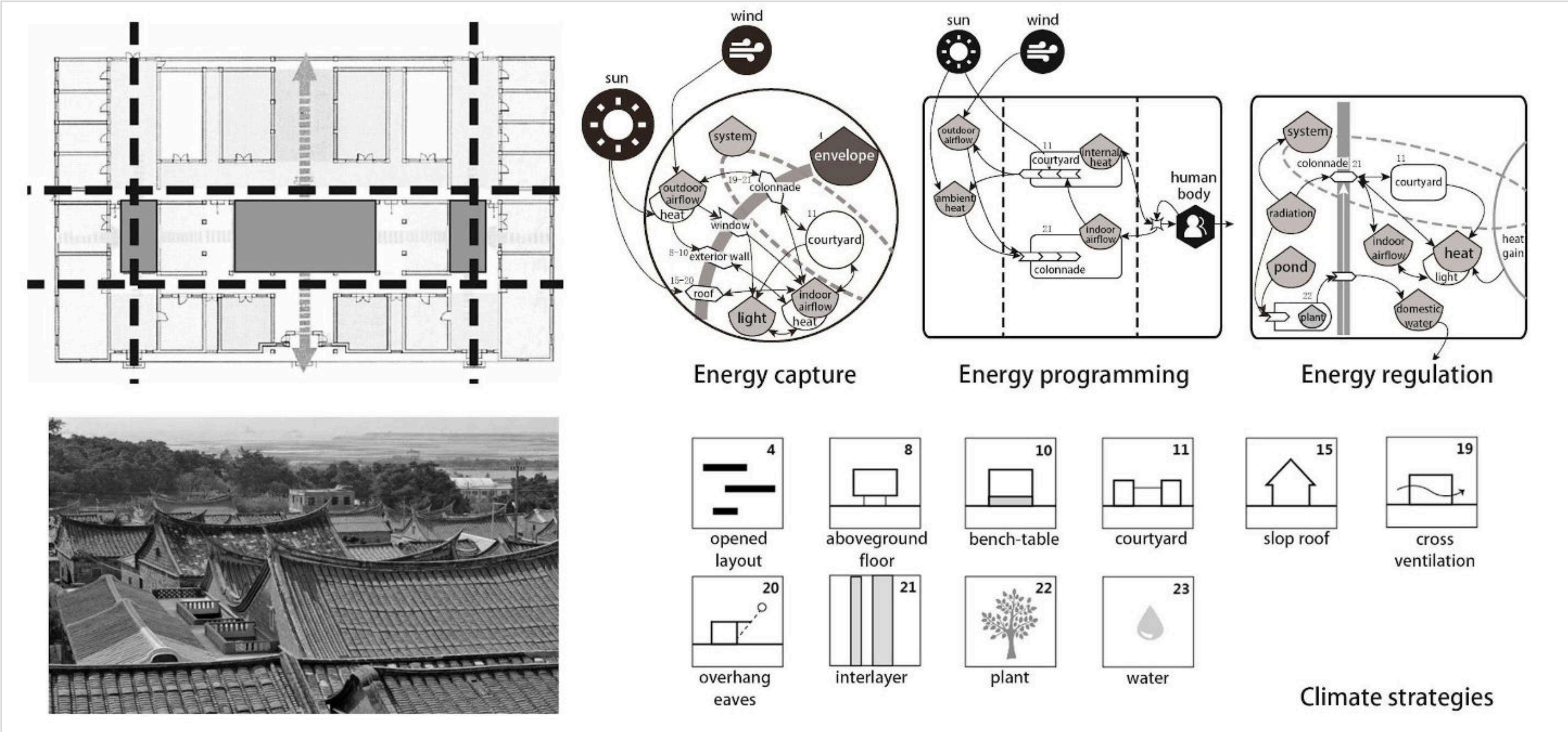

Figure 4: Diagram of climate adaption for Hushan Dacuo. Source: Simin Tao.

2—To assist in the climatic design of an infrastructure building

Dongying, located in the warm temperate zone and influenced by the marine monsoon, experiences dry and cold winters, windy springs, and hot, humid summers. The vernacular houses in Dongying typically have thick walls and small north-facing openings to address the climatic conditions. At the estuary of the Yellow River in Dongying, the Huanghekou Visitors Service Centre is a mixed-use infrastructure building that encompasses a reception area, ferry terminal and offices. In the pre-design phase, the use of energy systems language aids in identifying the building requirements, external climate characteristics, basic design prototype, and energy flow mechanisms, which serve as the foundation for further refinement (Figure 5).

Building Envelope Design: Based on the local climate characteristics, the primary consideration for climate adaptation in the building is insulation against cold. The building incorporates a unique double-layered rammed earth wall constructed using the water-based yellow sand from the surrounding area. The wall features small windows that provide effective protection against wind and cold while minimising the negative impact on the surrounding environment. This design approach also results in a gradient of colour texture that seamlessly blends with the wetland landscape of the site.

Internal Spatial Layout: The building has a slim form with a high aspect ratio dictated by the constraints of the site and function. To mitigate the effects of wind, the external walls feature small window openings. However, the building includes two rectangular courtyards of different sizes to facilitate natural lighting. The courtyards are connected by corridors, promoting natural ventilation within the building.

Facility Auxiliary Regulation: The two-story ferry terminal, located on the north side of the building, experiences high pedestrian flow and frequent use. In order to achieve uniform and gentle natural lighting, the roof above the hall incorporates staggered, electric-operated skylights, which optimise the light environment while allowing for manual control of indoor ventilation

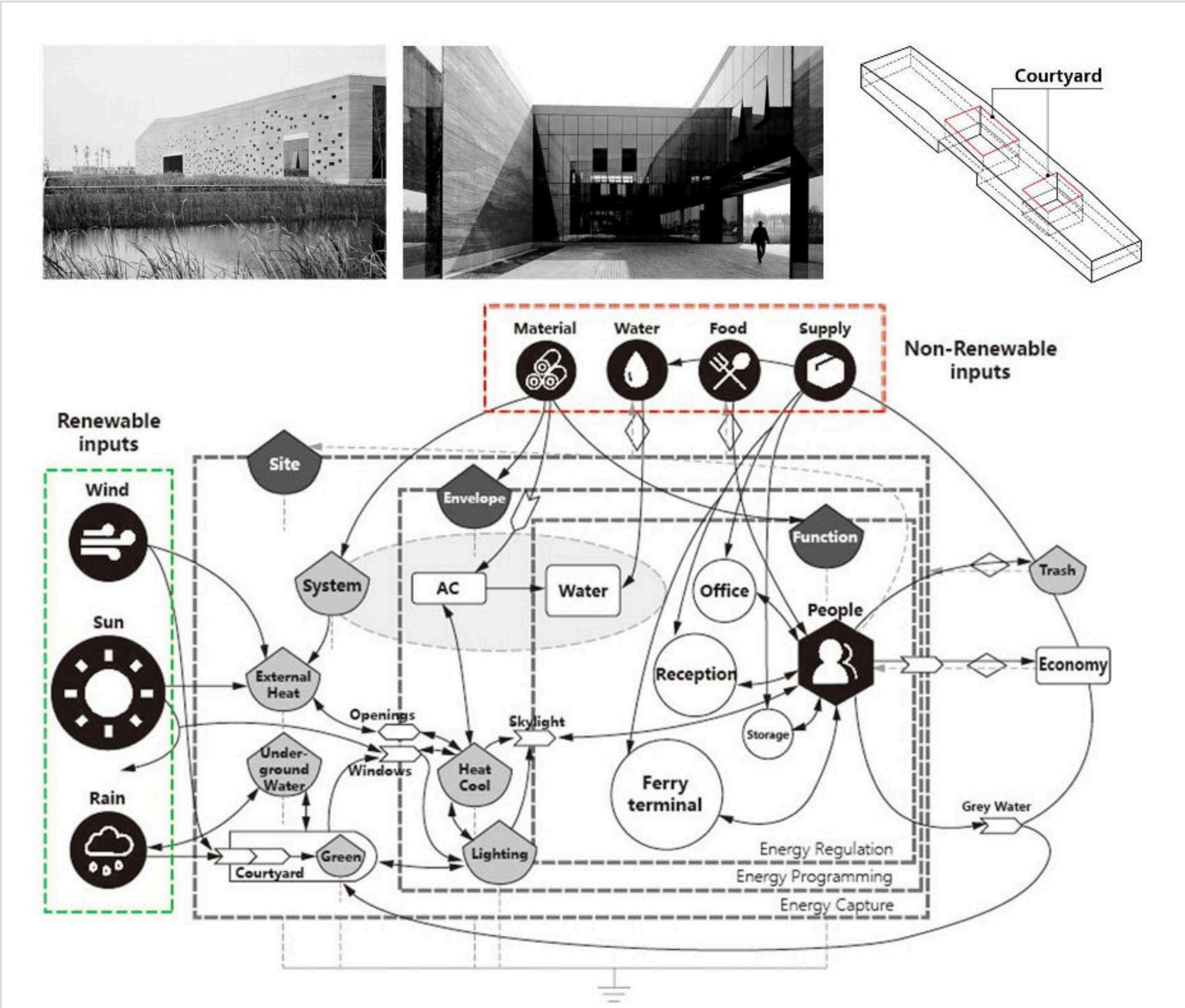

Figure 5: Diagram in design prototype for Huanghekou Visitors Service Center. Source: Simin Tao.

3—For analysing the POE of a public building

After the completion of a building, the analysis using energy systems language can be employed to establish the energy structure system of the building. This allows for a detailed examination of the intricate energy flow and distribution within the building's interior, facilitating the achievement of post-assessment objectives for the building. In this case study, the POE was conducted at the student activity centre at Nankai University, located in Tianjin, a city with a temperate monsoon climate characterised by hot, rainy summers and cold, dry winters (Figure 6).

The main components of the building are the auditorium and activity room, which are designed for student use. Additionally, there are several classrooms, offices, restrooms, service rooms, and storage rooms. The personnel can be categorised into two groups: non-fixed individuals, including students, audience members, and visitors, and fixed individuals, such as staff members.

When it comes to emergy evaluation, the largest portion comprises Depreciated Assets, accounting for 74%. The second-largest component is labour, which accounts for 11.8%. Following that is concentrated power, which is predominantly sourced from grid electricity, making up 9.8%. Consequently, it can be observed that the primary energy contribution stems from the construction of the building, driven by its substantial volume and extensive utilisation of construction materials

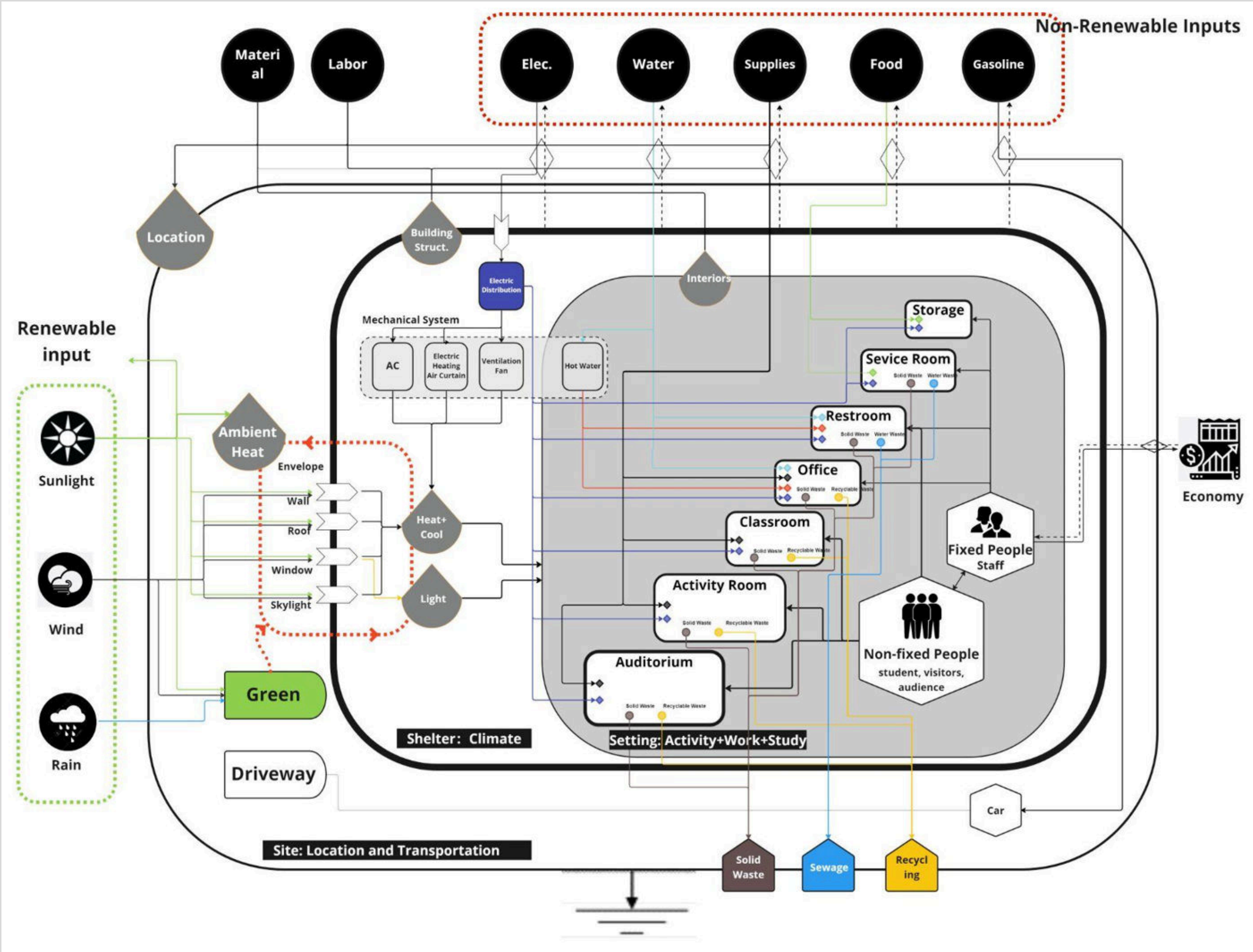

Figure 6: Diagram in POE of student activities centre of Nankai University.(Source: Qi Zhang.

Conclusion

Analysing the climate adaption of buildings from a thermodynamic perspective involves deconstructing architecture in terms of energy flow. Rather than viewing climate as physical elements such as wind, light, and rain, it is seen as different types and grades of energy sources that support the effective functioning of building systems. Architecture serves as a thermodynamic bridge between the climate and the human body, and through thoughtful design, energy can be effectively obtained, stored, and transformed.

In the current era, there is a plethora of environmental simulation tools and standards available to architects and researchers. However, creating a comprehensive context that considers natural, aesthetic, technical and social values on an equal footing is crucial. In this regard, energy systems language holds promise as an accurate and flexible assessment method for establishing correlations between climate and architectural form. It has the potential to provide a comprehensive thermodynamic perspective on climate, energy, form, and performance, taking into account the complexity of systems.

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