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Conceptual framework of NZEB energy management based on Petri Net modelling in the context of energy transition

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Abstract. The present paper aims to assess the operational complexity of nearly zero-energy buildings through a formal approach based on Petri net theory applied to discrete event modelling. It was intended to present the interactions between renewable energy production, energy storage, building demand and grid energy exchange by maintaining the logical connections that control energy management decisions. The paper addresses a subject related to the energy transition to a more sustainable energy system, in line with the European Green Deal and the Sustainable Development Goals to promote clean energy and climate action.

1 Introduction

Over the last years, the concept of Net Zero Energy Buildings (NZEB) progressed from a normative target to a challenging technical framework, which integrates energy efficiency, local renewable energy generation and adaptive operation strategies. Nearly zero-energy buildings are an important element of the energy transition, contributing to decarbonisation and resource efficiency, in line with the Sustainable Development Goals, especially Goal 7 which focuses on affordable and clean energy, sustainable urban development and climate change resilience. Through fostering high energy efficiency and integrating renewable sources, NZEB buildings will have a high relevance in the energy transition and the implementation of the European Green Deal.

A literature review [1] reveals that NZEB is an ambiguous concept that depends upon definitions, system limits (on-site vs. at-source) user profiles as well as performance indicators, leading to difficulties when comparing studies in this field and highlighting the requirement for transparent methods of modelling and assessment [2]. In this context, assessing NZEB performance often relies on energy indicators such as annual balance, specific consumption and energy self-consumption as well as operational components like flow management or grid integration.

The literature [3] addresses NZEB from the perspective of implementation and transition in specific climatic and regional contexts. In the Mediterranean region, a techno-economic and environmental assessment shows that achieving the net-zero target requires trade-offs between costs, emissions and technological configurations with results that are sensitive to operating scenarios and how storage or the grid is used.

The role of photovoltaic technology is acknowledged as a key factor in achieving the NZEB standard in residential buildings, even if actual performance depends on the time-based alignment of power generation and demand and thus highlights the importance of self-consumption, charging and discharging as well as export and import strategies [4]. Energy and comfort optimization studies emphasize that NZEB performance depends on indoor comfort and control approaches as well as on net energy [5].

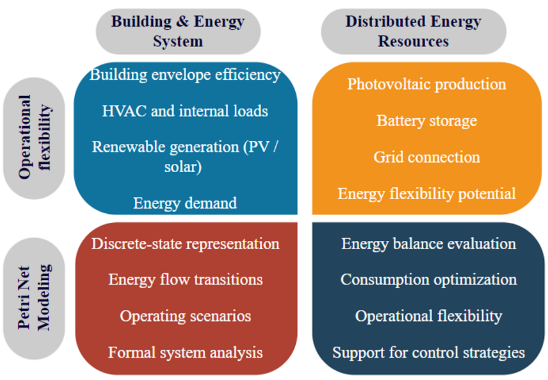

Fig. 1. Energy system and distributed energy resources.

The current trends in passive and material-based houses (such as PCM integration) show that NZEB buildings can be achieved through the combined use of building envelope, passive solutions and operational control and have significant energy, economic and environmental benefits [6].

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The NZEB scientific literature describes a wide range of energy analyses and optimizations. Among these, Petri Nets-based approaches can describe systems with discrete events, concurrency and synchronization, and provide a graphical and mathematical representation. A relevant example is the use of Petri Net for advanced energy management systems in smart buildings. This type of formalism aids to describe the processes and operational states [7, 8].

Recent study [9] highlights the increasing use of artificial intelligence and data-driven methods to support prediction and decision-making in complex systems in the building sector. This approach underscores the need for modelling frameworks in energy applications in the building sector.

This article aims to explore the operability of NZEB systems using Petri net-based discrete event modelling, highlighting the interactions between renewable energy generation, energy storage, building demand, and grid energy flow.

Petri nets are useful for modelling the systems that are characterized by concurrency processes, synchronization and resource sharing which are common in building energy systems. The graphical and mathematical formalism of Petri nets allows them to be used for formal analysis and qualitative interpretation, thus providing the ability to describe system behaviour directly without relying primarily on numerical simulation.

2 Power flow in the NZEB system and model assumptions

The NZEB concept is an integrated energy ecosystem consisting of four main subsystems: renewable energy generation (in this case, photovoltaic system), energy storage (battery), building demand and grid interaction.

In the model, the energy flows are expressed in discrete units, while we neglected the system losses, efficiency coefficients and performance limits. Hence, this model emphasizes the structural and logical aspects of energy management without focusing on detailed numerical analysis.

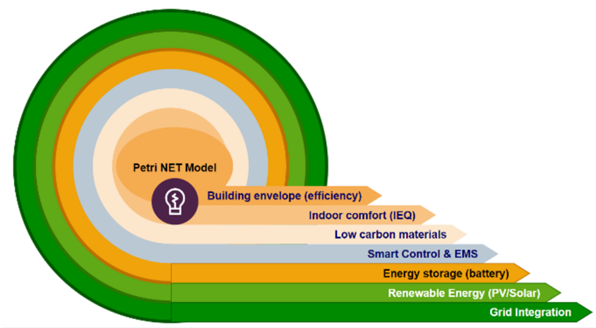

Fig. 2. Relevant elements for a Petri net model of NZEB concept.

The model created using the PNToolbox, in Matlab environment follows the essential operating principles of NZEB systems, including prioritising local renewable energy, battery storage and grid integration.

The system analysed in this study consists of a nearly zero-energy building (NZEB) with an on-site renewable energy generation system, electricity storage and grid connection. The building operates as an integrated energy network with locally generated energy, stored energy and external supply sources managed to meet internal demand while reducing dependence on the power grid [10 - 12].

The power flow within the NZEB is following a layered operating framework so that locally generated renewable energy sources are primarily used to supply the power required in the building.

The power flow within the NZEB is following a layered operating framework so that locally generated renewable energy sources are primarily used to supply the power required in the building. When power generation exceeds power demand, the surplus is stored in a battery system, which allows the energy to be buffered. When generation is insufficient, the stored energy will be used to supply the load, while the remaining deficit will be covered by energy imported from the grid. On the other hand, if both demand is supplied and storage capacity are maximized, then excess energy can be exported to the grid. This reflects an operational strategy typical for NZEB energy management systems intended to maximize self-consumption from renewable energy and minimize the dependence on external energy sources [13-16].

The coordination among subsystems is determined by an energy management strategy that indicates how energy flows can be controlled based on system conditions. The strategy ensures the optimal use of energy resources with continued reliability of supply [17, 18]. The discrete approach to modelling allows us to represent concurrent processes that occur simultaneously in the system and the transitions between different operational states.

2.1 Photovoltaic generation

The photovoltaic (PV) system represents the main local source of energy. It is assumed that its output is variable and depends on environmental conditions. In accordance with the operational logic of the system, photovoltaic output is prioritized for direct consumption and battery charging before any exchange with the grid. These actions reflect one of the main principles of NZEB in order to maximize the use of renewable energy in the building.

2.2 Building demand

The building load comprises the electrical energy required to support normal operation, including lighting, HVAC and appliances. This demand is modelled as a steady-state requirement and determines decisions concerning energy supply. The system pursues to satisfy demand primarily from local resources, relying on grid energy only when necessary.

2.3 Battery energy storage

The energy storage system helps balance the gap between renewable energy generation and demand. The battery is modelled by discrete state of charge (SOC) levels corresponding to low, medium, and high levels of energy. These states reflect the dynamic behaviour of energy storage and support the modelling of charging and discharging processes.

The storage system enhances the operational flexibility by allowing surplus renewable energy to be stored and used at times of low generation, reducing the power grid dependence.

2.4 Power grid

The power grid operates as a balancing system, assuring the availability of energy when local resources are limited and allowing the export of surplus energy. The bidirectional interaction of these two systems supports the reliability of the system itself and the integration of distributed renewable energy sources.

3 Petri Net theory

The initial state of the modelled system can be defined based on an initial marking, that specifies the distribution of tokens in the places of the Petri net at the beginning of the analysis. It represents the NZEB basic functional condition, and reflects the availability of energy resources and the state of the system before any dynamic evolution arises.

The Petri net is represented by a weighted graph consisting of places P and transitions T. The places represent the states of the system in terms of energy resources, while the transitions model events or processes that change these states. From a graphical point of view the locations are conventionally drawn as circles while the transitions are drawn as rectangles or bars providing a graphic distinction between static conditions and dynamic processes.

The nodes are connected using directed arcs defining the causality relation between places and transitions. Arcs can only connect a place to a transition or a transition to a place, ensuring the bipartite structure characteristic of Petri nets. Each arc corresponds to a positive integer weight indicating the number of tokens consumed or produced when the corresponding transition is fired. Within the proposed model, the weights correspond to either discrete energy quantities or logical activation conditions.

According to theory [8, 10], a marked Petri net is defined as a pair (N, M_0), where the structure N describes the topology of the system and M_0 specifies the initial configuration. The net (N, M_0) can be expressed as in Eq. 1÷5:

$$N = < P, T, W^-, W^+, M_0 > \quad (1)$$

where:

$$P = \{p_1 \div p_n\} \text{ depicts the positions;} \quad (2)$$

$$T = \{t_1 \div t_m\} \text{ depicts the transitions;} \quad (3)$$

$$P \cap T = \{\varnothing\}.$$

$$W^-: P \times T \rightarrow \{0,1,2, 3...\}; \text{ and } W^+: P \times T \rightarrow \{0,1,2, 3....\}; \quad (4)$$

$$M_0: P \rightarrow \{ 0,1,2, 3....\} \text{ depicts the initial configuration of the net.} \quad (5)$$

The paper analyses the Petri net based on the idea of an energy flow involved in an NZEB building, where tokens represent discrete units of energy or operational states. The places correspond to energy conditions or resources, such as photovoltaic availability, battery charge status and energy exchange processes. The transitions symbolize energy transfer mechanisms as well as control actions. This model addresses the differences between logical representations and physical energy flows and allows the analysis of system behaviour for operational logic and energy balance.

The Petri Net can also be represented by explicitly describing its components, as presented in Table 1 and Table 2.

Table 1. Petri Net state description (positions)

Position	Description	Relevance
p1	Availability of energy produced by the photovoltaic system	Available renewable energy
p2	Energy demand of the building	Active consumption
p3	Low battery charge level	Reduced supply capacity
p4	Medium charge level	Normal operation
p5	High battery charge level	Energy surplus possible
p6	Availability of the electricity grid	Battery backup
p7	Energy delivered to consumers	Direct supply
p8	Energy used for charging	Energy storage
p9	Energy exported to the grid	Excess energy
p10	Energy imported from the grid	Energy deficit

Table 2. Petri Net events description (transitions)

Position	Description	Relevance
t1	Use of PV energy to cover consumption	Available PV + active demand
t2	Charging the battery from excess PV	Available PV and low battery level
t3	Battery power used to cover consumption	Active demand and adequate battery level
t4	Export of excess energy to the grid	Available PV and charged battery
t5	Grid power used to cover consumption	Active demand and lack of local sources
t6	Increase in load level	Charging process
t7	Decrease in load level	Unloading process
t8	Clear Charging event	Synchroniza tion Reset

4 Petri Net modelling

The system model presented in Figure 3 is focused on the functional interactions between subsystems, and not on detailed physical modelling. Parameters including conversion efficiency, dynamic response times or power limits are not modelled as the main objective was to assess the operational behaviour and structural interactions of the NZEB energy system.

The model presents the energy management system logic of an NZEB and allows us to analyse how different subsystems cooperate to maximise self-consumption and ensure continuity of power supply.

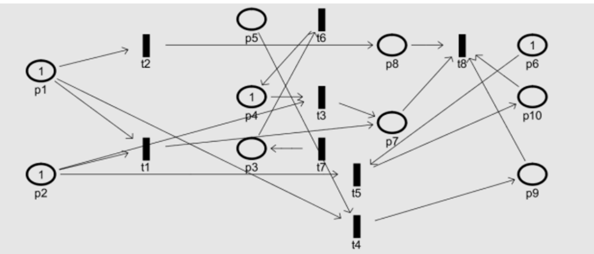

Fig. 3. Petri Net model.

4.1 Petri Model formulation and dynamic behaviour

Within the proposed Petri net, the structural relations are described by input, output and incidence matrices, used to achieve a mathematical representation of the energy flow logic. These matrices (W^-, W^+, W) facilitate the analysis of the evolution of the tokens and the properties of the system.

$$M_{0\,(Pi)} = [1 \quad 1 \quad 0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0]$$

The Petri Net model illustrates how an energy-efficient building is able to manage energy consumption with four components: photovoltaic production (P1), building consumption (P2), battery storage (P3–P5), and grid integration (P6, P9, P10). For each discrete simulation step, the energy demand (P2) activates the need to supply the load and the system selects the available source based on the available resources.

$$W^- = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{bmatrix}$$

$$W^+ = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Using the incidence matrix, the system marking resulting from the firing of transitions (the occurrence of events from T1 to T8, as described in Table 2) was determined:

$$W = W^+ - W^- \tag{6}$$

$$W = \begin{bmatrix} -1 & -1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 \end{bmatrix}$$

If PV (P1) is available, self-consumption is prioritized through T1, which means that PV energy is delivered to consumers (P7). If there is surplus photovoltaic energy, the surplus is transferred to the battery using T2, creating a charging event and then the state of charge increases using T6.

When there is insufficient energy from PV to cover consumption, the battery can be used to supply power though T3, providing energy to consumption (P7) and, as a result, reducing the state of charge through T7.

If the battery is fully charged and results an excess of energy, the surplus can be exported to the grid by firing T4, marking the event as export (P9). The operational events (P7–P10) can be reset at the end of the step by firing transition T8 to ensure discrete dynamic and prevent event accumulation.

In Figure 4, transition T5 (grid supply) is activated when a request is received from the building (marked with P2) and the grid is available (marked with P6), but local energy sources are insufficient to supply the load (i.e., photovoltaic or battery supply cannot be activated). In this situation, T5 acts as the NZEB backup mechanism and its activation produces a token in P10, indicating that the energy is imported from the grid to cover the deficit.

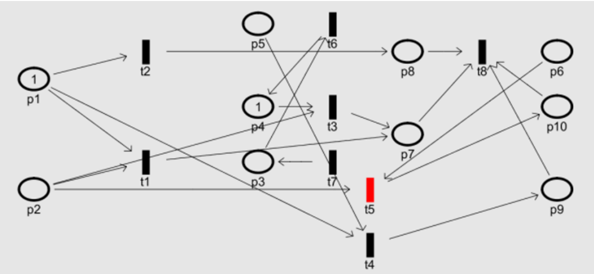

Fig. 4. Petri Net status before firing transition t5.

In Figure 5, the transition T7 is activated when battery energy is used to supply energy consumption, after T3 activation and indicates that demand is powered from storage. T7 activation highlights a system response when energy is withdrawn from the battery, an event that reduces the state of charge (from P4 to P3) and reflects the discharge process within the NZEB energy management logic.

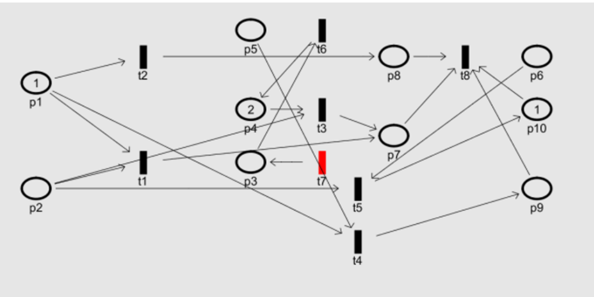

Fig. 5. Petri Net status before firing transition t7.

In Figure 6, T2 is activated in the presence of surplus photovoltaic energy in order to charge the battery and transfer energy to the storage subsystem.

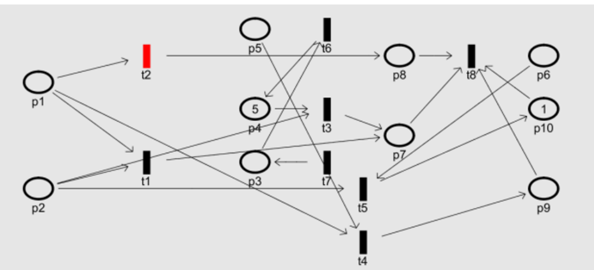

Fig. 6. Petri Net status before firing transition t2.

The T8 transition acts as an assimilation transition that removes tokens from event nodes representing operational outcomes. It does not produce tokens in any node and serves as a synchronization mechanism, indicating the end of a discrete operating process.

4.2 Reachability tree

The reachability tree in Figure 7 and 8 emphasizes the possible operational states of the model starting from the initial marking (M_0), revealing that multiple transitions can be activated depending on energy availability.

The tree structure reflects the different possible ways of supplying energy, such as direct consumption of photovoltaic energy, battery charging, battery discharging or import from the grid.

From this state, several transitions (T1, T2, T3, T5, and T7) are enabled showing alternative operational scenarios of the energy management system.

The tree structure reflects alternative energy management paths and highlights that the system can evolve without structural blockages showing the consistency of the proposed Petri Net model.

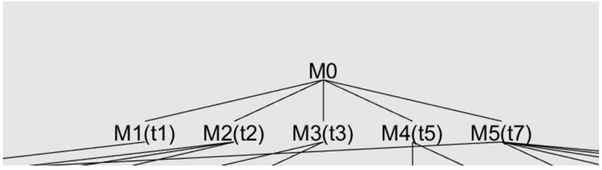

Fig. 7. The reachability tree (initially activated transitions).

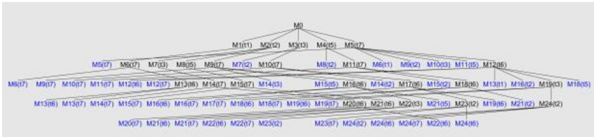

Fig. 8. Petri net reachability tree.

5 Conclusions

The present study highlights that the operation of NZEB systems can be effectively explained through a hierarchical energy flow structure, where locally generated renewable energy has priority to cover the demand, which is followed by the use of storage, grid power and the export of surplus energy. These priorities align with the operational objective of NZEB facilities which is to maximize self-consumption and minimize grid-based energy supply.

The proposed Petri net model illustrates a formal framework of discrete events that can be used to describe the coordination between generation, storage, demand and power grid highlighting the operational logic and behaviour of the system.

The accessibility analysis indicates that the system changes between operational states without leading to deadlock, implying that at least one transition remains active under normal operating conditions. Activation of transition T5 in the accessibility tree indicates that the grid is used as a backup supply in line with the operational logic of real NZEB systems.

The proposed model addresses concurrent processes, such as simultaneous demand supply and battery charging, showing that the Petri Net formalism is suitable for energy management systems. The simulation shows that the relation between production, consumption, storage and the power grid can be viewed logically through the evolution of the tokens.

The Petri Net model framework provides a versatile approach for future development of the system, enabling the integration of real operational data, efficiency parameters and control or optimization strategies. It also can be coupled with numerical simulation tools to enhance the practical applicability.

In the context of the energy transition, analysing the behaviour of NZEB aids in a better understanding of how building energy systems can be structured in line with the targets of the European Green Deal and SDGs related to clean energy, sustainable cities and climate action.

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