Embodied energy and life-cycle greenhouse gas of conventional and the resilient nest house

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Abstract, This study performs the comparative assessment of the initial embodied energy and life-cycle greenhouse gas (GHG) emission between Thailand’s conventional reinforced concrete (RC) house and the Resilient Nest house which was designed and constructed for the Solar Decathlon Europe 2019 competition. The Resilient Nest is a prototype for the sustainable house and an alternative building in perspectives of renewable-energy, green building, energy efficient, and net-zero waste house. This house was designed and constructed by KMUTT team with an integration design of cozy house and the green economic system concept which have become a major concern nowadays for mitigating the environmental impacts due to an urban development. The environmental sustainability performance was investigated. All the materials used for conventional and the Resilient Nest houses as well as the energy used for the construction, were evaluated to illustrate the embodied energy (MJ) and GHG emission (kgCO₂eq). As per square meter of the usable space of the house, the results show that the Resilient Nest house has embodied energy of 2,302.2 MJ/m² and life-cycle greenhouse gas is about 122.22 kgCO₂eq. Whereas, the conventional house is illustrated the consequences of embodied energy of 1,400 to 3,580 MJ/m² and 300 – 4,625 kgCO₂eq per square meter. The Resilient Nest house clearly proofs the minimizing environmental impact than the conventional house. The designation of materials was considered as an important parameter. In addition, as the whole life-cycle, the higher impact from the initial phase would be minimized and compensated during the service phase. To enhance the ultimate goal of the Resilient Nest house, recommendations for further improvement of the prototype house have been discussed.

1. Introduction
The traditional Thai houses were built with timber because of its aesthetic, and ease of manufacturing and construction. But the later regulation limits the using of some hardwood timber to reduce the deforestation issues. Afterwards, the reinforced concrete (RC) was raised as a construction material because of its durability and cheaper construction cost. But the comparison between the timber and the RC houses through the end of their life-cycle, the greenhouse gases were presented in RC houses greater than the timber houses [1]. Using RC consumes tons of embodied-energy and has net carbon emission over 8 times higher than using timber [2]. There are a lot of Rubberwood (H. Brasiliensis) remains after 20-25 years harvesting its latex. These remained woods are not being used. Therefore,
King Mongkut’s University of Technology Thonburi (KMUTT) purposed to use the Rubberwood as a building material with objectives of adding value to the remaining Rubberwood, and to reduce the embodied-energy and life-cycle greenhouse gas from the construction industry.

The Resilient Nest was designed and built by students and faculty advisor of KMUTT to participate the Solar Decathlon Europe 2019 (SDE19) competition at Szentendre, Hungary [3]. Solar Decathlon is an international competition for university students which has 10 contests [4] related to the sustainability solar-powered house design, construction, and operation. Since the concept of the Resilient Nest was a rooftop house which could be constructed on top of an existing building, the lightweight material should be used. The Rubberwood was introduced and used in design and construction of the Resilient Nest because of its lightweight with the density of 560 – 625 kg/m³ [5]. Moreover, the Resilient Nest was concerned about embodied energy and greenhouse gas (GHG) emission of the major building material in the stage of raw material extraction, production, transportation, and construction. The results of the embodied energy and life-cycle greenhouse gas emissions of the Resilient Nest compared with the conventional RC house could proof the using the Resilient Nest as an alternative building in future for minimizing the environmental impact in the urban areas.

2. Methodology
One of the well-known methodology used for computing the results of the embodied energy and GHG emission is the process-based method [6,7] which was carried out for the analysis of the Resilient Nest and the conventional RC house. The processing of these embodied energy and GHG emission were focusing on the initial embodied energy which covered the system boundary of cradle-to-site including the 6 main materials of structure, insulating, floor, structural foundation, wall, and ceiling components as shown in figure 1 [8]. The processes flow which are including the raw material extraction, production, transportation, and construction was the consideration parameters of this method.

![Figure 1. System boundary](image)
2.1 Functional Unit
For the ease of comparison between the Resilient Nest and the conventional RC house, the area of each dwelling was defined as the functional unit in square meter. Consequently, the embodied energy was expressed and compared in a unit of energy per area (Mega joule per square meter, MJ/m²). The total gross area of the Resilient Nest was 96 m².

2.2 Embodied Energy
The embodied energy analysis was emphasizing on the raw material extraction, production, and transportation phases in accordance to the Inventory of Carbon and Energy (ICE) [9] database excluded the construction stage which was separately evaluated which is discussed further. The overall embodied energy used in the raw material extraction, production, and transportation phases \( EE_i \) of the 6 main materials used to constructed the Resilient Nest can be determined by this following equation:

\[
EE_m = \sum (m_i \times EE_i)
\]

(1)

where \( m_i \) and \( EE_i \) are mass of elements \( i \) needed in the building and embodied energy coefficient of the material \( i \) [10]. Therefore, every material’s information has to be collected from the Resilient Nest as inventory and used to compare with the existing RC house data.

2.3 Life-cycle Greenhouse gas assessment
This study has adopted embodied carbon as a carbon footprint of construction materials. This means consideration amount of greenhouse gases released throughout the processes of cradle-to-site including these raw material extraction, production, transportation, and construction processes. Thereby, the consequences are converting to the life cycle carbon emission; the presence of carbon dioxide (CO₂) causes global warming which is damaging to the environment. Thus, the results from embodied carbon are expressed as CO₂ equivalent for all stages. The overall carbon used during all phases \( EC_m \) of the materials used in the Resilient Nest can be determined by this following equation:

\[
EC_m = \sum (m_i \times EC_i)
\]

(2)

where \( EC_i \) is embodied carbon coefficient of the material \( i \) [10]. The embodied energy coefficients and embodied carbon coefficients are shown in table 1.

| Material               | Embodied Energy, \( EE \) (MJ/kg) | Embodied Carbon, \( EC \) (kgCO₂eq/kg) |
|------------------------|-----------------------------------|--------------------------------------|
| Softwood               | 7.4                               | 0.45                                 |
| recycled polypropylene | 43-52                             | 2.0-2.2                              |
| Ceramic tile           | 9                                 | 0.59                                 |
| Particle board         | 9.5                               | 0.51                                 |
| Vinyl flooring         | 68.6-79.1                         | 2.29                                 |
| Fibre cement board     | 10.9                              | 2.11                                 |
| Polycarbonate          | 103-114                           | 5.7-6.3                              |
| PU/PIR                 | 72.1                              | 3                                    |
2.4 Transportation stage

The transportation of the Resilient Nest was considered from the percentage by weight (kg) of materials quantities. The embodied energy and greenhouse gas were significantly affected by the transportation of the massive major components of the Resilient Nest which is Rubberwood as a structural material. The embodied energy for material transportation \((EE_T)\) and the greenhouse gas emission as CO\(_2\) equivalent emission during the transportation stage \((GHG_T)\) are expressed in equation (3) and (4) respectively.

\[
EE_T = 1.66 \cdot \sum (m_i \times EE_i' \times D_i)
\]

\[
GHG_T = 1.66 \cdot \sum (m_i \times EC_i' \times D_i)
\]

where \(D_i\) is the transportation distance of the building material \(i\) from the plant to the construction site in kilometre (km) which was specifically from the wood processing factory to Bangkhunthien campus of KMUTT, \(m_i\) is the quantity of material \(i\), \(EE_i'\) (MJ/km-ton) is the energy consumption per kilometre of vehicle for a ton of material \(i\), and \(EC_i'\) (CO\(_2\)eq/km-ton) is the CO\(_2\) equivalent emissions per kilometre per ton of material \(i\) [10].

2.5 Construction stage

The previous research showed that the embodied energy of the construction was approximately 269 MJ for the construction site area of 12.6 to 52.92 m\(^2\) with forklift with other heavy machines [11]. The Resilient Nest was design with an integration of architecture and construction to optimize the energy consumption and manpower during the construction stage. Every house's components are small and lightweight, so it can be constructed without using any heavy machine which can reduce huge amount of embodied energy and greenhouse gas emission. In addition, there were several equipment used during the construction such as electrical driller. Therefore, the energy consumption during the construction stage depends on workers and the equipment.

3. Results and discussions

The initial embodied energy of the Resilient Nest was evaluated from a major of building materials which considered the weight of materials as figure 3. The ratio shows the percentages by total weight. The illustration represents that the major material of the Resilient Nest is a structure which made from Rubberwood and it governed the amount of embodied energy and greenhouse gas.

![Figure 2. Percent of materials building by weight](image_url)
The initial embodied energy evaluation of the raw material extraction, production, transportation, and construction phase are illustrated as figure 3(a). The life cycle greenhouse gas was derived from the embodied carbon. As well as the embodied carbon from inventory carbon and energy that was expressed from the life-cycle carbon so the change of embodied carbon would assess as a greenhouse gas and resulting in figure 3(b). As per square meter of the usable space of the house, the results show that the Resilient Nest house has embodied energy of 2,302.2 MJ/m² and life-cycle greenhouse gas is about 122.22 kgCO₂eq. Since Rubberwood was the highest amount of the Resilient Nest's material of 88.96%, it played the important role in consuming the energy of 1,440.9 MJ/m² and emitted highest greenhouse gas of 81.7 kgCO₂eq which are over 62.6% and 66.9% of the overall materials used. Nevertheless, the high amount of embodied energy can illustrate the high amount of life cycle greenhouse gas.

![Embodied Energy](image1)

![Embodied Carbon](image2)

**Figure 3.** Amount of (a) initial embodied energy from material building
(b) Life-cycle greenhouse gas as carbon dioxide emission

Comparing to the previous study of Zhou and Azar [10], the total initial embodied energy consumed by the RC was about 2,950 MJ/m² which was significantly greater than the Resilient Nest of 1.28 times. The conventional RC house is illustrated the consequences of embodied energy of 1,400 to 3,580 MJ/m² and 300 – 4,625 kgCO₂eq per square meter [10, 12-14]. The Resilient Nest house proofs the minimizing environmental impact than the conventional house. In addition, as the whole life-cycle, the higher impact from the initial phase would be minimized and compensated during the service phase which the Resilient Nest met the target of Net-Zero Energy Building (NZEB) and generated energy from the solar radiation. In the other word, during the service phase the Resilient Nest does not have to consume any more energy at all. Although the embodied energy and life-cycle greenhouse gas of the Resilient Nest were reduced from the conventional house, but this prototype was constructed with materials which assist the contest. For further improvement, the material used for the construction could be selected with the lower energy consumption and less structural material would be used for residential or house.

### 4. Conclusions

1) The overall initial embodied energy and the life-cycle greenhouse gas of the Resilient Nest less than the conventional house up to 1.28 times because of the construction phase which was design to be constructed with an only man-power instead of heavy machine. With the improvement of
reducing material used, the overall initial embodied energy of the Resilient Nest could be more reduced.

2) The life-cycle greenhouse gas was assessed from carbon which derived from embodied energy evaluation, the high amount of embodied energy can illustrate the high amount of life cycle greenhouse gas.

3) The Resilient Nest will promote using the Rubberwood as a construction material which will reduce the embodied energy and the life-cycle greenhouse gas due to the construction industry. Moreover, the agriculturist could have more chance to make a profit from the remaining wood.

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