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Environmental impact evaluation of energy saving and energy generation: Case study for two Dutch dwelling types

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ABSTRACT

The existing building stock is a logical target to improve the level of sustainability of the built environment by energy saving measures. These measures typically entail a decrease of operational energy demand, mainly by adding building components such as insulation packages and energy generating devices. Consequently, material related environmental impact might create a collateral disproportionate burden, which is not well addressed in current assessment methods. In an attempt to evaluate this effect, two common dwelling types in the Netherlands, a terraced and a detached dwelling, have been redesigned to the level of Zero Energy Building in four scenarios, and the environmental impact of these scenarios has been assessed, expressed in embodied energy and related to the carrying capacity, expressed in embodied land ($m^2 \cdot a$). The lowest environmental impact is achieved in the scenario with an average U-value of 0.29 W/m^2K and 35 m^2 and 75 m^2 of PV modules for the terraced and the detached dwelling, respectively. In this scenario, added embodied energy is 3.4 GJ/m^2 and embodied land is 308,777 $m^2 \cdot a$ land for the terraced dwelling and 5.2 GJ/m^2 and 653,644 $m^2 \cdot a$ land for the detached dwelling. This evaluation indicates that a focus on only energy efficiency improvement shows a collateral material related environmental impact which should be embedded in the complete environmental assessment of buildings.

1. Introduction

Worldwide, the consumption of energy and material resources is increasing significantly to maintain, and even improve, our standards of living. Between 1973 and 2012 the global final energy consumption increased from 4672 Million tons of oil equivalent (Mtoe) to 8979 Mtoe and is expected to grow to 12,001 Mtoe in 2035 [1]. 20%–40% of this global final energy consumption is attributed to the built environment, more than 86% of this consumption is based on fossil fuels [2].

In the Netherlands, the residential sector accounts for approximately 17% of the total primary energy consumption [3]. The residential energy consumption consists of 74% natural gas and 2.5% renewable energy sources, 18.9% of which is solar energy [4].

Global developments such as the depletion of fossil fuels, climate change and social-economic issues, emphasize the need to improve energy efficiency. In this respect, targets have been set in the European Union (EU) to achieve a lower overall energy consumption in the built environment and to decrease dependency on fossil fuels. Being a main agent, buildings are crucial towards achieving the EU objective of reducing greenhouse gas emissions by 80–95% by 2050 compared to 1990 [5]. The EU Energy Performance Building Directive (EPBD) requires all new buildings to be nearly Zero Energy Buildings (*nZEB*) by the end of 2020 and existing buildings should be *nZEB* in 2050 to meet European targets [6,7]. A *nZEB* has a very high energy performance and the very low remaining amount of energy required should be covered to a very significant extent by energy from renewable sources, produced on-site or nearby [6]. The implementation in legislation of *nZEB* in the EU leaves room for interpretation on a member state level. In a Zero Energy Building (*ZEB*) all necessary energy is generated on site based on renewable sources, possibly by means of connection to a storage medium or the grid for balancing over days, seasons or the year [8–10], however consensus on EU level is still to be developed on the exact definition. There are a number of long-term

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Nomenclature

COP	Coëfficiënt Of Performance
EE	Embodied Energy
EPBD	Energy Performance Building Directive
EU	European Union
FEC	Final Energy Consumption
LCA	Life Cycle Assessment
LC-ZEB	Life cycle Zero Energy Building
Mtoe	Million tons of oil equivalent
nZEB	nearly Zero Energy Building
OE	Operational Energy
PEC	Primary Energy Consumption
PV	photovoltaic
RE	Renewable Energy
STC	Standard Test Conditions
Wp	Wattpeak, nominal power at STC of PV modules
ZEB	Zero Energy Building

advantages of a *ZEB*, such as lower operating and maintenance costs, better resilience to natural disasters, better resilience to power outages and a higher level of energy security [10]. Considering the EU economy, renovation of existing buildings is a win-win option because it has implications for growth and jobs, energy and climate and cohesion policies [11].

A *ZEB* can be realized by lowering the energy demand of the building, for instance through better insulation, and by generating energy at the building scale, for instance by solar energy systems. Both strategies have implications for the building envelope as this is the building part that determines heat losses and gains and also provides the necessary area for the installation of solar energy systems [12,13]. Solar energy is seen as one of the most promising alternative sources to meet our energy demands [14]. However, for the realization of higher insulation levels of for the realization of solar energy systems, materials are needed. Worldwide, 50% of all extracted materials are used in the built environment [15], and the extraction of building materials has increased with 30% between 1995 and 2005 [16]. In general, buildings have a linear pattern of resource consumption resulting in disposal ('from cradle to grave'), without qualitative or quantitative recycling or re-use of these resources [17]. In a linear pattern, raw materials are extracted and used in the realization and operational phase, after which they are mostly not re-used at all in the decommissioning phase, or are used at lower quality levels, called *down-cycling*. This may not cause a deficit of resources if all these materials are renewed or renew themselves in their effective lifespan. At this moment, many countries import more materials than they produce themselves [18]. This might lead to an intensified international competition for raw materials [16]. Design philosophies such as *Cradle to Cradle* and the *Circular Economy*, attempt to adapt the linear process into a circular one by re-using or recycling materials [19,20].

One of the indicators in the field of environmental assessment is embodied energy; the amount of energy necessary to process raw materials, modify materials and transport materials [21–24]. In this way, the operational energy and the embodied energy in materials can be evaluated at the same scale.

For instance, extremely low energy buildings have a total of ca. 900 MJ/m^3 for heating over 30 years and have a total of 1400 MJ/m^3 embodied energy, indicating the share of materials in the environmental assessment with this indicator [23,25]. Other recent studies show the significance of increased embodied energy due to the addition of insulation materials and installations [22].

In most buildings, embodied energy is seldom evaluated, or only evaluated after completion, and to date there appears to be no universal methodology to assess the total embodied energy of a building [21,26,27]. Current embodied energy databases show a large bandwidth of results for the same materials, among others due to the different calculation methodologies [21]. This is illustrated in Fig. 1, in which the embodied energy per m^2 is shown for different buildings and different climatic zones, ranging between 3.6 and 8.8 GJ/m^2 [22].

Furthermore, embodied energy is not considered in both the EPBD and the Dutch energy agreement for sustainable growth [28]. Hence, being more energy efficient in the built environment might prove to be deceptive when following current policies and tools including embodied energy based on Life Cycle Assessment (LCA). However, it could be argued whether calculating all aspects into only energy generates the needed insight in the environmental impact of buildings.

On the track towards *ZEB*s, the performance of building materials will become more important because they create the only environmental impact once the operational energy will be completely generated on site, and therefore they should be part of the assessment [29,30]. Because both materials and energy interact and influence the final environmental impact of a building, a joint evaluation is necessary. Thus, the environmental assessment should generate insight in the level of sustainable production of materials, and not only in energy, which can be related to the carrying capacity and expressed in land footprint [31]. In future, land necessary to produce renewable energy might compete with land necessary for food production and material production, which may lead to other choices in the design and realization of buildings [32].

In the Netherlands, the dwelling stock has a turnover smaller than 1% each year, complying with the energy performance regulations, making the existing building stock one of the key sectors where action is needed to meet energy efficiency goals [33–36]. As the focus on energy efficiency has mainly emerged after the first oil crisis in 1973, many dwellings, especially from before this time, are characterized by poor energy efficiency. 58% of Dutch dwellings are built before 1975 [37]. As many of these dwellings are still technically and socially adequate for housing, ways for sustainable renovation are being investigated [38]. The quest is to find the optimum between reduction of energy demand and generation of energy demand, in terms of lowest environmental impact of energy performance and material consumption [39]. Until 2012, in approximately 17% of the existing Dutch dwelling stock energy efficiency improvement measures have been realized to decrease energy consumption with 20%–30% [40].

To investigate the combined environmental impact of energy performance and material consumption, expressed in two indicators, embodied energy and embodied land. The environmental impact is assessed of four successive renovation scenarios of insulation levels and associated surface of PV modules for two existing dwelling types in the Netherlands. The dwelling types are the terraced dwelling built between 1946 and 1964 and the detached dwelling built before 1964 [36,37] due to the large energy consumption and large number of these dwelling types. The insulation packages are based on 100% renewable materials to minimize material related environmental impact. The environmental impact of the original state of the dwelling types itself is outside the scope of this study. The environmental impact is related to the carrying capacity – the amount of land-time necessary to create the materials used for both energy saving and energy generation, based on the MAXergy methodology [41,42], the BINK tool [43] and the ICE database on embodied energy [44]. The impact indicator of carrying capacity based on the MAXergy methodology is expressed in