Applied Energy 162 (2016) 11–20

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Energy performance and economic viability of advanced window technologies for a new Finnish townhouse concept

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HIGHLIGHTS

- Whole building simulation to determine the energy performance of selected window cases.
- The economic viability of advanced windows was investigated from end-user perspective.
- It is economical for end-user to pay additional investment price for advanced window.
- Location of a building influences the economic viability of advanced window.

ARTICLE INFO

Article history:
Received 17 June 2015
Received in revised form 18 September 2015
Accepted 6 October 2015

Keywords:
Advanced window
Townhouse
Economic viability
Life cycle cost
Building energy

ABSTRACT

Among the elements of a typical building envelope, windows are responsible for the greatest energy loss due to their high *U*-value. Conventional windows tend to have poor glazing properties, which causes significant heat loss during the winter season and undesirable heat gain during the summer season. Advanced window technologies are therefore required to mitigate the energy consumption of buildings. The key hypothesis in this study is that advanced windows become economically viable for end-users if the difference in life-cycle cost between advanced window types and the state-of-the-art (reference) window is equal to zero. To verify this hypothesis, we calculate the allowable additional investment costs (dIC) for three types of advanced windows over a given life span. Different advanced windows; electrochromic, PV and vacuum windows together with a self-cleaning feature were compared with a state-of-the-art window with excellent properties (reference window) in terms of energy performance and life-cycle cost for a conceptual residential house (i.e. townhouse) in Finland. By performing a whole-building simulation using IDA ICE, the impact of these windows on the total delivered energy needs of the townhouse were estimated. Among the alternatives, the vacuum window (lowest *U*-value) offers the highest dIC value, due to its maximum energy savings. With a generic efficiency of 6%, the PV window holds the intermediate position between the vacuum and reference window in terms of dIC value. Hypothetically, with a *U*-value of 0.6 W/m^2 K, the PV window would become the most energy efficient window alternative. The self-cleaning feature proved to be a dominant factor toward the increase of dIC value by avoiding maintenance costs. Electrochromic glazing is not economically feasible due to its negative dIC value as it doesn't offer life cycle cost savings.

1. Introduction

Buildings account for approximately 40% of the EU's energy consumption [1]. According to Gustavsen et al., a two-story residential house with 30% of the walls covered by windows accrues up to 60% of its total energy loss through windows [2]. The house complies with the standards of the 2007 Norwegian building codes, with a window *U*-value of 1.2 W/m^2 K. The window is commonly the weakest part of the building envelope in terms of energy performance due to its high *U*-value (up to 2.0 W/m^2 K) in comparison to the walls, roof and floor (<0.3 W/m^2 K) [3]. On the other hand, the energy performance of a window is also affected by the solar heat gain coefficient (SHGC), solar transmittance and visible transmittance; which, in turn, have an impact on cooling energy, heating energy and daylighting/visual comfort. DeForest et al. [4] concluded that the electrochromic window can provide meaningful energy savings; ranging from 5–11 kW h/m^2 y for commercial and 8–15 kW h/m^2 y for residential buildings in different climate zone in the United States. Electrochromic glazing is a type of smart

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http://dx.doi.org/10.1016/j.apenergy.2015.10.056

glazing; the other types are liquid crystal and suspended particle device [5].

A lot of recent research has been done toward the development of advanced windows with maximum energy performance and visual comfort [6–11]. Another key trend of development is the integration of innovative materials, such as self-cleaning nanostructures [3] and transparent solar photovoltaic materials in windows [12–14]. In the literature, the following types of advanced glazings have been identified as the most attractive, namely; electrochromic (EC) glazing, photovoltaic (PV) integrated glazing, self-cleaning glazing, and vacuum glazing [5]. Particularly, PV glazing is considered very promising since it allows the window surface to be harnessed to PV generation and simultaneously prevent overheating due to the solar heat load [12].

In the EU Directive 2010/31/EU, the EU Member States agreed that by the end of 2020 all new buildings are to be nearly zero-energy buildings, i.e. buildings with a high energy performance, where a significant proportion of energy needs will be covered by local (on-site) renewable energy sources [15]. Here, the governing design principle is cost-optimality, i.e. finding the design solution with the lowest life-cycle costs per heated square meter over a given period of time, including the structures and systems that affect the energy performance of the building (*E*-value). Since the analysis period is 20 years [16], the development of technology and the market needs to be predicted. The advanced window technologies studied here are at various stages of market development, from early commercial products to laboratory prototypes. Due to early market and developing technology, the manufacturer's price estimates are high. For example, the current price of the EC is around 800 €/m^2 [7], which is approximately 500 €/m^2 higher than the price of the state-of-the-art commercial window [17]. Using the present cost levels in economic analyses would induce a biased figure of the economic viability of advanced windows and hence would indirectly prevent the transition to new technology.

The novelty of this study is the prediction of allowable additional investment costs of advanced windows over the reference window with an alternative perspective, based on the hypothesis that that advanced window still remains economically viable for end-users in comparison with the state-of-the-art window. In other words, the research aims at pointing out the life cycle cost savings that can be obtained by using advanced windows due to improved energy performance and lower maintenance costs, in comparison with the best available commercial window. This life cycle cost savings plus the cost of available commercial windows is equal to the installed cost of economically viable advanced windows for end-users. None of the past studies have addressed this issue of the economic viability level of advanced windows from the perspective of the end-user. Additionally, a new residential building type (i.e. townhouse) located in Helsinki has been considered as a case study to investigate the energy and economic performance of advanced windows through dynamic energy simulation and an extensive economic analysis. There is no tradition of townhouses in Finland; therefore the typology of the target building is new.

2. Methodology

2.1. General

In this study, a whole-building simulation is performed followed by an extensive economic analysis. The methodology includes five steps to achieve the objective of the study. In step 1, a selection of window systems was performed to form Cases. In step 2, the target building (i.e. townhouse) simulation model was created in IDA ICE, a dynamic simulation software. In step 3, the modeling of variable glazing properties (Solar heat gain coefficient and transmittance) along with the simulation of window Cases was performed. In step 4, the delivered energies for all window Cases were calculated using post-processing of the simulated annual heating, cooling and electrical demands. In step 5, the associated costs of delivered energy for the implemented window Cases were calculated, and finally life cycle costs were evaluated.

2.2. Simulation software

The target building was modeled and simulated using the IDA-ICE building simulation software. The software was originally developed by the Division of Building Services Engineering, Royal Institute of Technology (KTH) and the Swedish Institute of Applied Mathematics, ITM [18]. IDA-ICE has been validated by EN 13791 [19,20]. The study of Travesi et al. conducted on the empirical validation of models of five simulation tools, including IDA-ICE, concludes that the agreement between measured and simulated data was good [21]. The performance of IDA-ICE has been tested and validated by several authors [22,18,23]. It has been chosen as one of the major 20 simulation programs and subjected to analysis and comparison [24]. In IDA-ICE, there are options available to model dynamic glazing properties (i.e., by changing key window properties based on control schedules).

In the IDA ICE simulation environment, heat balance equations are solved by the finite difference method [25,26]. The IDA-ICE software allows the modeling of multi-zone buildings, HVAC systems, internal loads, and outdoor climate among others, and provides dynamic simulation of heat and air flow with a variable time-step. Building construction models with various geometries can be drawn or imported from CAD programs via IFC files. It is a suitable tool for the simulation of thermal comfort, energy consumption and daylighting in complex buildings. Helsinki–Vantaa (TRY 2012) climate file was used for the energy simulation [27]. The TRY2012 climate files contains hourly data of outdoor temperature, relative humidity, direction and speed of wind, direct solar radiation and diffuse solar radiation over a whole year (8760 h). The data is originated from different calendar years between 1980–2009 and represented as typical as possible by performing mean values, frequency distributions [27]. It is to be noted that the PV window uses the same climate file to calculate its electricity output.

2.3. Modeling of variable solar heat gain coefficient (SHGC) and transmittance for electrochromic glazing

Karlsson [28] modeled the control strategy of variable EC properties according to global vertical irradiance, indoor air temperature and occupancy pattern. Jonsson and Roos [29] also considered occupancy pattern in formulating the control strategy for EC glazing. Furthermore, there were several studies which deal exclusively with the control strategy of EC glazing [30–32]. By understanding these studies, a simple control strategy is implemented which is based on solar irradiance in terms of time of the day and internal occupancy rates. It is important to note that similar control schemes are also used for the blinds in other window cases in order to facilitate a fair comparison. Simplified control offers the possibility to avoid additional costs as the main scope of this study is to evaluate the economic viability.

The variation of solar heat gain co-efficient (SHGC), solar transmittance and visible transmittance is modeled and controlled by way of multiplying factors varying between 0 and 1 according to the scheduled timing of the desired effect. IDA-ICE offers an option to change the value of a variable in the simulation by adopting control schedules, i.e. a stepwise input to change the parameter. Fig. 1 shows the variation of the visible transmittance value over a typi-