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Sustainable business model of affordable zero energy houses: Upscaling potentials

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ABSTRACT

In 2018, the average number of occupants per dwelling is steadily decreasing, creating a demand for small, affordable housing. According to European Union energy targets, new small homes should be energy efficient. However, data clearly shows that energy efficient homes are mostly unaffordable and there is an urgent need to design and build small affordable zero energy homes. However, a sustainable business model for small affordable zero energy homes has not yet been developed in European countries. The Housing 4.0 Energy project explores the development of affordable zero energy homes in three countries: the Netherlands, Belgium and Ireland. This study explores the business models and potential for scaling up the five schemes (Ireland operates three schemes in different counties). The results of this study may be useful to practitioners, policy makers, and small families facing the problem of affordable zero energy homes. The Dutch scheme targets a market of self-builders of low-middle income households. In the Flemish scheme, non-profit social rental agencies provide the houses for low-income groups. In Ireland, local authorities provide social housing for applicants on waiting lists. The Business Model Canvas (BMC) is used to analyse the business models for affordable zero energy homes in these countries. Data is collected mainly through interviews and focus group meetings with experts. The results show that all schemes create environmental, social and economic sustainability values for low/low-middle income households by providing energy efficient, comfortable and affordable homes. Several barriers to the upscaling of these homes were identified, such as cultural barriers in design, building materials, as well as legal and technical barriers. The technical barriers can be addressed in a relatively short time, but overcoming cultural and behavioural barriers might be more difficult. Engaging government, market participants, and providers can accelerate the development of these schemes. Examples of different schemes and the courses developed during the project can be used to disseminate the results of the business models of these schemes. Finally, the business models of the schemes can be modified and adopted for the development of affordable zero energy homes in other countries.

1. Introduction

The European Commission is aiming for cost-effective ways to become more climate-friendly by reducing energy consumption. Two milestones are assigned to cut emissions by 40% by 2030 and 60% by 2040 (Commission, 2017). Furthermore, all the new buildings should be nearly zero energy. Industrial countries, such as England and Germany are among the major producers of Greenhouse Gases (GHGs). Therefore, on top of agreed targets at EU level, the North-West Europe (NWE) countries have defined tighter national targets. In these countries, the housing sector has a significant share in total energy consumption and consequently production of GHGs. In these countries, the distribution of the population and the household sizes are changing. More people prefer and can afford to live alone compared to the Southern and Eastern European countries.

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[1] Overburden rate is the percentage of the population with affordability issues. Households have affordability issues when they spend more than 40% of their incomes on housing (Eurostat, 2017).

[2] https://www.nweurope.eu/projects/project-search/h40e-housing-40-energy/.

[3] The German scheme is not the focus of this study, as the German scheme has recently started and aims to design a show model house for small zero energy houses.

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Across Europe, policies to make housing affordable have reduced the overburden rate significantly[1] (Haffner and Elsinga, 2015). However, still a large percentage of the population is facing affordability issues, even in the NWE countries. In the Netherlands, Belgium and Ireland, 11%, 9% and 4% of households respectively had affordability problems in 2019 (Eurostat, 2018). Therefore, developing sustainable innovative approaches for providing affordable houses for one/two person(s) is essential. The Interreg North West Europe project the Housing 4.0 Energy (H4.0E)[2] aims to develop affordable innovative zero energy homes in the Netherlands, Belgium and Ireland[3] through sustainable innovation. This H4.0E project adapts and applies new digital and low-carbon technologies that benefit both consumers and providers. The aim is to reduce carbon emissions and improve the quality of life for people in NWE and beyond.

Sustainable innovations refer to "innovations that can improve the (environmental, social, and financial) sustainability performance" (Carrillo-Hermosilla et al., 2010). The definition of sustainable innovation covers products, services and technologies, as well as new business and organisational models (Charter et al., 2008; Brehmer et al., 2018). This study focuses on innovative business models of small affordable ZEHs and the essential institution and industry structure (size, experience, constraints by non-economic institutions, etc.) (Katz and Shapiro, 1985; Shapiro and Varian, 1998). A Business Model (BM) demonstrates an abstract representation of the enterprise. The goal of a business model is to evaluate the end-user needs and ability to pay, to determine the manner by which the enterprise addresses and delivers values to end-users, to persuade end-users to pay for value, and to transform those payments to profit through the proper design and operation of the various components of the value chain (Teece, 2010; Osterwalder and Pigneur, 2010; Chesbrough and Rosenbloom, 2002).

The current business models are not suitable for providing small affordable, as well as zero energy houses with the highest standard[4] in NWE countries. These business models usually impose high costs on the investors. As a result, investors ask for higher prices/rents. Therefore, there is a need for developing innovative business models which allow for affordable sustainable housing (Teece, 2010). The institutions and the industry structure are very important for the success of the business models. New businesses cannot develop and extend without the institutions (regulations, policy incentives, values, norms, and beliefs) that support their activities. In the case of new technologies, the institutions usually need to be adapted or invented (Nelson, 1994).

Identifying the main components of a suitable innovative BM for providing small affordable energy efficient houses will facilitate the faster development of these houses. It also acts as a complementary approach to the product innovations. The aim of this study is to (a) analyse the business models of three case studies in the Netherlands, Belgium, and Ireland, and (b) to assess the upscaling potential of the innovative business models by considering the industry structure and the institutions surrounding these businesses. The Business Model Canvas (BMC) is used as a visualisation tool to describe different components of a BM and to explain the interrelations between these components (Osterwalder et al., 2004; Osterwalder and Pigneur, 2010). This contribution explores schemes in early stages and applies a framework that combines the business models, industry structure, and institutions. The data are mainly collected by semi-structured interviews, reports, workshops among the partners, and focus groups.

The remainder of the paper is structured as follows: Section 2 reviews the recent literature on business models (BM), BM innovation and sustainability, upscaling, industry structure, and institutions. Additionally, the BM archetypes of the schemes are illustrated. Section 3 explains the data collection method. Sections Section 4, 5, and 6 then present the results of the analyses (Section 4), discussion on these results (Section 5), and conclusions (Section 6).

[4] For example, currently, social housing associations provide nearly zero houses.

2. State-of-the-art

2.1. Business model (BM)

The term BM is widely used since the mid 1990s, due to the rise of the internet economy (Muzellec et al., 2015). However, there is no single and unique definition of BM due to application in many fields with different perspectives (Zott et al., 2011; Pateli and Giaglis, 2004; Shafer et al., 2005). BM initially is defined by Timmers (1998) as "the modelling of key components of a business including product/service, actors, roles, information, revenue and benefit". A BM has continued interaction with the available institution and industry structure to ensure compliance with regulations and adapt to the size and distribution of the market. Chesbrough (2010) emphasised that a great BM is more valuable than a great innovative technology. A distinction can be made between the BMs in the following ways: (a) taxonomy, bottom up: capturing the features of real businesses in the world. In some cases, enterprises practices are more advanced than academia in developing innovative BMs. (b) typology, top down: representing abstract ideal types of business based on theoretical and conceptual studies; (c) a combination of both. These archetypes can therefore be used as the basis for different types of analysis (Baden-Fuller and Morgan, 2010; Bocken et al., 2014; Sarasini and Linder, 2018).

In this research, the Osterwalder' BM Canvas (BMC) is adopted, which has been widely used in academic research and practices (Bohnsack et al., 2014; Joyce and Paquin, 2016; van Waes et al., 2018). BMC is a visual modelling approach, consisting of nine building components: key partners, activities, resources, value proposition, customer relationships, channels, customer segments, revenue stream, and cost structure (profit formula)[5] (Osterwalder et al., 2004; Osterwalder and Pigneur, 2010). Table 1 explains different components of the BMC.

2.2. Business model innovation and sustainability

Business Model Innovation (BMI) is a new area of research and a fundamental component in the context of sustainability transitions by for instance smoothing the adaptation of sustainable energy technologies to the new target customers. The aim of BMI is to facilitate the sustainability transition by providing economic, social, and environmental sustainable BMs. A successful BMI should be able to create significant positive and/or reduced negative impacts for the environment and/or society, through modification of the existing BM. The components of a sustainable BM comprise measurable environmental and social values in the value propositions, appropriate distributions of costs and benefits among actors, and a customer interface stimulating the customer in terms of sustainable consumption (Schaltegger et al., 2016; Boons et al., 2013; Lüdeke-Freund and Dembek, 2017). It is not only about changes in the products/ services through new technologies, but also creating new systems by changing the way that enterprises do business (Amit and Zott, 2012; Bocken et al., 2014).

Different BMs with the same bundles of technologies can have significantly different social and/or environmental impacts resulting from the ways they create, deliver, and capture value (Wells, 2013; van Waes et al., 2018; Sarasini and Linder, 2018). A sustainable BM should be economically profitable (adequate return on investment) while reducing the environmental and socio-economic difficulties by providing socially relevant products/services. BMI can modify a BM into an innovative BM by introducing new interconnections in the innovation network between the innovation agents (enterprises, bankers, investors, research institutions). The innovation network and its interconnections are the sources of market creation for an innovation (Boons and Lüdeke-Freund, 2013). Moreover, new opportunities for value creation can

[5] It also consists of four pillars: product, infrastructure management, customer interfaces, and financial aspects.

Table 1
Description of different components of business model Canvas.

Component	Description
Value proposition	Products/services and value proposition offered to the market
Customer segment/ relationship	Business' target customers, approach in delivering the products/ services, and building a strong relationship with them (business to business, (B2B))/(business to customer, (B2C))
Key partners	The network of suppliers and partners that make the business model work
Key processes	Particular actions/steps essential for a business model to facilitate the delivery of the value proposition
Key resources	The most important assets
Profit formula	The revenue model and the cost structure

References: Osterwalder et al. (2004), Osterwalder and Pigneur (2010).

be discovered through changing current operating activities. To design innovative BMs, an outside-in approach, using completely new archetypes of businesses, and an inside-out approach, exploring the potential changes of the current BM, can be used (Joyce and Paquin, 2016).

2.3. Upscaling potential, industry structure and institutions

Jolly et al. (2012), Drury et al. (2012), and van Waes et al. (2018) examined the potential upscaling of innovative BMs for adoption of sustainable energy technologies. Following Jolly et al. (2012), in this research, three different aspects are considered for upscaling: (a) reaching a new customer segment of the ZEHs, specifically households with affordability issues (e.g. the low income/lower middle income and small households); (b) changing existing institutions in a way that facilitate the upscaling of ZEHs; (c) replicating the BM, by promoting and establishing new enterprises. The potential upscaling of a BM can be explained by economies of scale on the supply and demand side. Supply-side economies of scale are realised whenever the cost per unit of a product/service decreases as the number of customers increases. This can depend on the experiences of suppliers and investors, as well as the size of the enterprises (Katz and Shapiro, 1985; Shapiro and Varian, 1998).

A digital platform can provide information, for example, about the production costs or the design of a product. This platform connects the supply and demand sides of the market. As the number of high quality suppliers (on the platform) increases, the platform becomes more attractive to the demand side. However, in order to continue the business operation of the digital platform, two challenges need to be overcome: (1) attracting providers and end-users to the digital platform, and (2) attracting a sufficient number of end-users. The first challenge is also known as the chicken-and-egg problem. The platform owner must find ways to bring both sides onto the platform. Suppliers on the supply side will not participate without end users on the demand side and vice versa (Evans, 2003; Ebrahimi et al., 2018).

The digital platform is a core part of the H4.0E project. This platform enables the customer-centric design of the houses. It also directly calculates costs, predicted energy consumption and embodied carbon for end users through various tools integrated into the platform. The H4.0E platform can significantly contribute in upscaling the AI ZEHs through the development and use of the digital platform. Advertising the platform by government agencies and umbrella organisations of housing users and manufacturers can help overcome the challenges in attracting sufficient numbers of suppliers and end-users.

The costs of innovative technologies and new sources of energy influence the upscaling potential of zero energy houses. These technologies often contribute in reducing CO_2. Therefore, the government supports the application of innovative technologies and replacing traditional energy sources with renewable energy sources. For example, the cost of renewable electricity sources has fallen substantially in recent years in the Netherlands. Also, in the Dutch climate agreement, the

Table 2
Cost reduction trajectory for renewable electricity sources (Ministry of Economic Affairs and Climate Policy, 2019).

Euro/MWh	2020	2021	2022	2023	2024	2025
Wind energy on land	59	55	52	50	49	47
Solar - PV	83	78	73	68	63	58

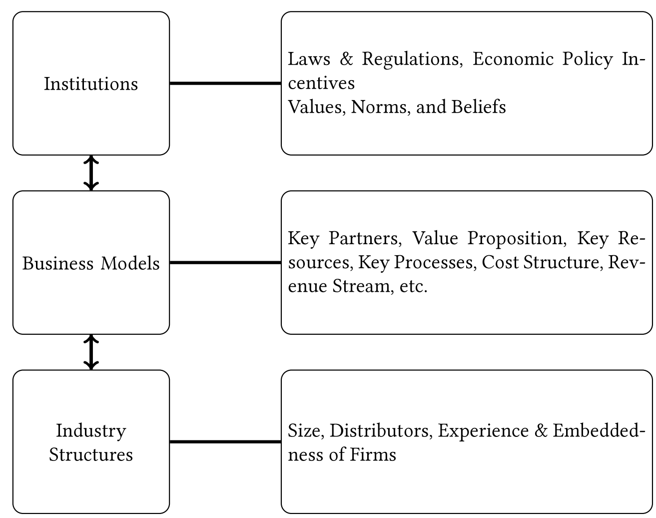

Fig. 1. Business model in the context of institutions and industry structures for evaluating upscaling potential.

parties agreed to achieve a diminishing cost trajectory for Solar–PV and wind speeds for wind energy on land. Table 2 shows the decreasing costs of renewable energy sources stated in the Dutch climate agreement (Ministry of Economic Affairs and Climate Policy, 2019).

Institutions refer to a rather solid group of rules and practices, embedded in structures of resources that provide the environment for doing activities. The activities and resources together with the associated institutions (regulations, norms, and cultural-cognitive factors) contribute stability and meaning to social life. The BM is built on a foundation of regulations to ensure value creation in compliance with Law. The regulations cover both the highly regulated rules/ laws at national levels or less regulated types of governing in terms of planning and visionary documents at local and regional levels (Olsen and March, 1989; Scott, 2013). Norms are described as specifying "how things should be done" as well as "legitimate means to pursue valued ends" (Scott 2014: 64f). In the H4.0E schemes, norms play an important role even for the construction materials that we will explore in Section 4. Fig. 1 shows the conceptual framework of this study consisting of BMs, institutions, and industry structure.

Table 3
Canvas business model, industry structure, and institutions for analysing the different archetypes.

BM types	Value proposition	Customer interface	Profit formula	Industry structure	Institutions
$PrSe^2$ (e.g., Almere)					
Pr^3 (e.g., Flemish)					
Pu^2Pr (e.g., Irish)					

Pr: Private, Se: Self, Pu: Public.

2.4. Affordable innovative zero energy housing business model archetypes

The bottom-up approach is followed in this research to describe the business archetypes of three countries. The schemes of three different countries are studied to design the archetypes of AI-ZEHs. In the city of Almere in the Netherlands, the homeowners build the houses and the land is privately-owned. The Almere case is the first scheme that is planned to be implemented and the experiences will be used by the schemes which follow it. 13 houses are planned to be built in the first phase and in the second phase, another 14 houses. The energy efficient technologies, such as solar PV-panel are chosen by the self-builders based on their decision-making criteria, e.g. between more environmental friendly and initial investment costs vs. operating costs (energy costs) of technologies. The initial investment costs are higher because of relatively expensive innovative technologies. However, energy costs will be lower by using the innovative technologies in the long-term.[6]

In Belgium, in a former recreation zone, Huldenberg in the province of Flemish Brabant, the private land owners communicate with Kamp C who is the coordinator for building these houses. A cooperative company (Everywhere Architecture) is responsible for the design of six small houses with one and two bedrooms up to 76 m^2 to rent them for social housing. Therefore, the approach is a combination of private buildings and social renting. Per two units, the same package of innovative technologies is planned to be installed. In this case, the government supports the private land owner in changing the recreation zone into a permanent residential site.

In Ireland, three schemes are planned for Wexford County, Carlow County, and County Kilkenny. The Projects in Carlow and Kilkenny will go on site first, followed by the site in Wexford. The units will be constructed for people on the social housing waiting lists. The Council aims to learn from H4.0E partners and shift from a traditional building process into an innovative building process of producing low carbon small houses. Similar approaches are followed in Carlow County and County Kilkenny. In all counties, the landowners are the local authorities (county council) and the buildings will be built by a private contractor. The houses will remain under the ownership of the local authorities and will be maintained by them while providing the houses to households from the social housing waiting lists.

Based on the information of the schemes in three different countries for the low and lower-middle income households, three archetypes are developed. Private land owner, self-investor and self-builder ($PrSe^2$), private land owner, private investors, and private constructor (Pr^3), and public land owner, public investor, and private constructor (Pu^2Pr) (Fig. 2).

The BMC is used to describe and test the different archetypes of the case studies in three countries. The institutions and industry structure of the schemes are evaluated to explain the environment in which these archetypes will be implemented. The institutions cover the regulations, policy incentives, values, norms, and beliefs. The industry structure includes the size, experiences, and constraints by non-economic institutions (Table 3).

Pr: Private, Se: Self, Pu: Public

[6] Based on the regulations of EU and the Netherlands, the new buildings should be at least nearly zero.

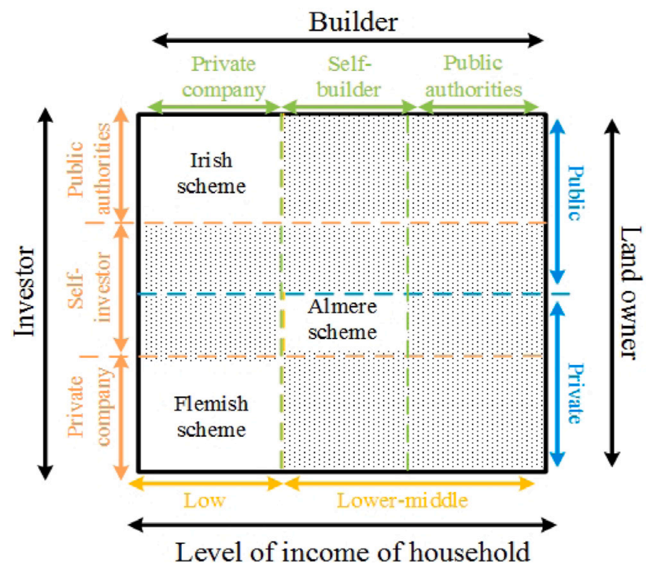

Fig. 2. Business model archetypes of affordable innovative zero energy houses in three countries.

3. Data collection

The BMs and the role of different institutional contexts in these schemes are explored through semi-structured interviews.[7] In the semi-structured interviews, the questions about the components of the BM and the upscaling potential are modified based on the answers of the previous interviewees and some additional (more specific) questions are asked. The semi-structured interviews lasted approximately 1–1.30 h.[8] The interviewees are experts involved in the implementation of the project, either as part of the prototyping (especially in Almere) or as part of the actual project. The interviewees have different roles within the project, including project manager, architect/designer, construction cost engineer, communicator with clients, social housing expert, renewable energy/circular building expert, housing construction expert, building regulations expert/building engineers. Other sources of data collection include the focus group meetings in each region among stakeholders on the financial and institutional barriers to each scheme and the semi-annual project workshops among project partners.

4. Results and analyses

4.1. The Almere scheme, an example of private land owner and self-investor

4.1.1. Business model components

Table 4 presents the BMC for the Almere scheme. The main value proposition in the case of Almere is providing the possibility for the

[7] The names of the interviewees are in Appendix A.

[8] The questions can be found in Appendix B. For the case study in the Netherlands the interviews were conducted face-to-face, while for the other case studies the interviews were conducted virtually to avoid long travel distances.

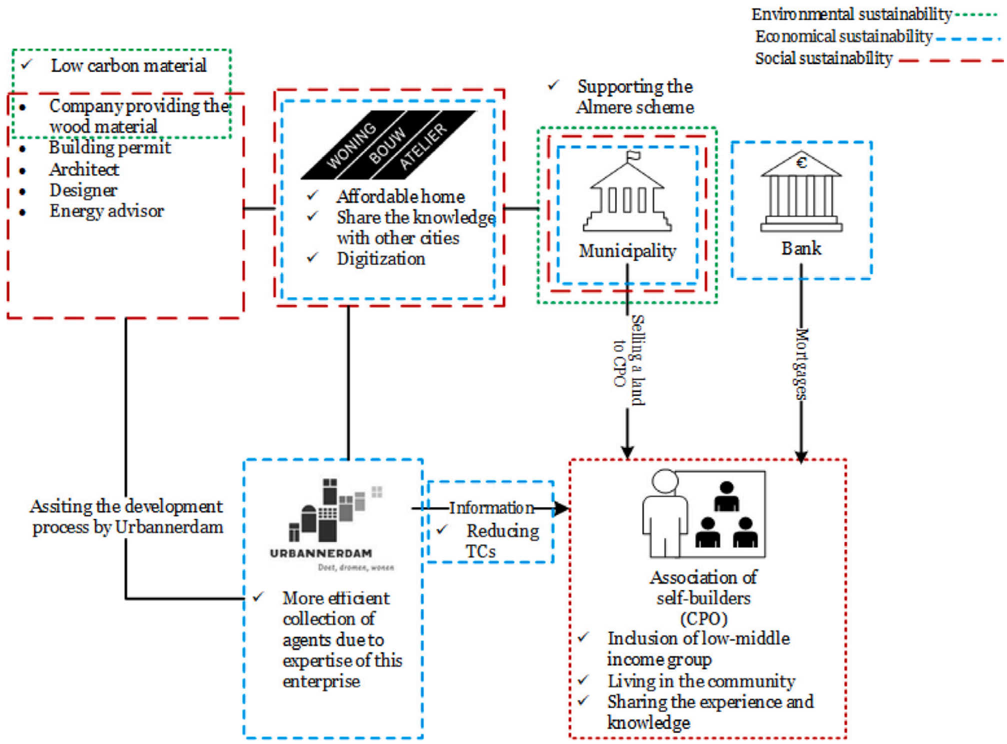

Fig. 3. Different types of sustainability values in the Almere scheme.

lower-middle income groups to build their own houses in a new community. This group of people can hardly afford to buy regular houses and they are not often eligible/they have to wait for a long-time to rent a house from the social-housing sector. From the societal perspective, living in a community is an opportunity for the self-builders. Self-builders can share their knowledge and experiences in the building processes. They can share responsibility in the neighbourhoods, e.g. making it more environmental-friendly. From the environmental perspective, the choice of construction materials is low-carbon, e.g. circular timber frame structures. Regarding the profit formula, the aim is to reduce the costs via digitisation, shared procurement (larger quantities lead to lower prices), and eliminating the labour costs. The self-builders collectively hire the architect, energy adviser, etc.

The Woningbouwatelier, a public organisation with experience in self-building, identifies and hires all the necessary experts in the Stripmaker neighbourhood to help self-builders build. The self-builders have made a sustainable Collective Private Commissioning (CPO). Urbannerdam,[9] an independent, specialist consultancy, works with the CPO of the Almere scheme to facilitate the development process. It helps and advises each household in managing the process, making decisions, monitoring planning and overseeing a good financial settlement. Woningbouwatelier, Urbannerdam, etc. offer services subsidised by the municipality of Almere. Technion, an independent and specialised consultancy, has developed three energy concepts that self-builders can choose between, depending on their installation skills and budget. Compared to the other concepts, the passive house contains less installation work and consists, for example, of a ventilation system with heat recovery. The main communication channels of the Almere programme with potential future self-builders are newsletters from the municipality, online (e.g. funda.nl) and through marketing campaigns (see Fig. 3).

[9] https://www.urbannerdam.nl/.

4.1.2. Industry structure

The Almere scheme faces the following challenges for the future development of AI-ZEHs in the Netherlands: (a) Land costs are relatively high in the Netherlands. In the Almere scheme, the price of land depends on the value of the house. Indeed, a fixed ratio between land price and house value of 20%–25% is fixed. Recently, the actual land prices have increased due to the sharp increase in house values in the Dutch housing market. Ultimately, self-builders will have to pay more for land than the estimated land prices of a few years ago. Moreover, the growth rate of income is lower compared to house values. So given the mortgage conditions, self-builders are getting into financial trouble.

(b) The use of a timber frame building requires precise construction to make the houses stable. In the Netherlands, concrete is usually used instead of timber frames, so there is not much experience with timber frame buildings.

(c) The initial investment cost of energy efficient technologies, such as PV panels, is relatively high for this particular group of households (lower middle income) because their financial budget is limited. Although the installation of these technologies results in lower energy costs and lower overall costs in the long run, the higher initial costs affect mortgage options, especially for the targeted lower-middle income group. The adoption of these technologies by larger companies can reduce costs for CPOs (see Table 5).

4.1.3. Institutional and the building process barriers

Institutions. The combination of self-build and zero energy houses is relatively new in the Netherlands. Therefore, from an institutional point of view, there are several obstacles to the expansion of the Almere scheme. These barriers can be divided into different hierarchical levels: *(a) National government: building regulations.* For a long time, the government has set the standards and subsidies for the construction industry. Newly built self-build homes are subject to similar or even more flexible building regulations than existing homes. However, self-build building use flexible concepts, such as WikiHouse. Therefore, these concepts need to be accepted before upscaling at national level (based on the interview). *(b) Local government: planning.* The municipality of Almere

Table 4
Business model Canvas (BMC) of the Almere scheme.

Concept	Description
Value proposition	Choice freedom in designing their dwellings (not for the place), locally adaptable, low-carbon materials (timber frame structure+no big machines are used), customised form and layout, digitisation, sharing knowledge/experience/open source.
Customer segment/ relationship	Middle income group (€36k–€45k gross yearly income) In the 1st phase: 13 houses; 2nd phase: 14 houses. Online, and websites. In the future: a planned marketing campaign.
Key partners	Self-builders, Almere Council/Woningbouwatelier, WikiHouseNL, contractors for foundations, energy advisers/consultants, designers, Urbannerdam experts
Key processes	Two parallel processes: Process A: main responsibility by other actors, e.g. coordinator (1) Coordinator contacts people, (2) Group will be selected, (3) Architect helps them in the design with the toolbox (swift system). (4) Request permit, (5) The coordinator might hire someone to lead the construction, Process B: main responsibility by end-users The self-builders hire different subcontractors for building foundations.
Key dilemmas	• Culture and inflexibility of the traditional system to include an innovative approach. • Friction between energy efficient measures and affordability.
Key resources	• Financial: mortgages. Woningbouwatelier, Urbannerdam, etc. provide services that are subsidised by the Almere municipality. • Human: self-builders, Urbannerdam enterprise, building industry (company providing timber frame structure, architect, designer), municipality of Almere, WikihouseNL, Wikifoundation UK • Physical: the building method consists of wooden plywood that is milled to size using a CNC router after which they are put together on site through self-build. • Digital platform: providing information, e.g. material
Profit formula	• Lower price: digitisation, shared procurement, open source (i.e. reuse of data from previous developments) eliminating a large part of labour costs: around 20%–25% cheaper of the total costs • €165–230k price of the house in the phase 1.
Institutions	land policy (availability of land for self building depends on the municipality) and residual accounting of land prices (high house prices lead to high land prices)
Industry structure	• Using the digital platform (in the second phase and upscaling the Almere scheme)

Table 5
The Industry structure for upscaling the small affordable zero energy houses.

Facilitating the upscaling of BM	Prohibiting the upscaling of BM
Guidelines for the self-builders	**L**ack of experiences on the small ZEHs combined with the self-building
Eigenbouw Information Center (ICEB)	Combination of the following factors:
Growing numbers of self-building	**A**pplying a land quote
Digital platform	**S**harp rising house prices
	Higher land prices for the low-middle income group.
	Constant/slower households' income growth

has a more flexible attitude towards all kinds of new experiments like the development of small zero energy houses (WiKiHouse) compared to many other municipalities in the Netherlands (Almere, 2020; Feary, 2020).

From the interviews, although the initial investment costs for innovative technologies could be reduced by implementing shared concepts, such as shared solar panels and district heating, the national legislation supporting shared innovative technologies, is still lacking. For example, for shared PV panels, external or virtual net billing is not allowed (Huijben and Verbong, 2013). *(c) Residents: culture/quality of living.* From the interviews, it appears that culture and habits play an important role in the further development of AI-ZEHs. For example, many consumers are hesitant to switch to these technologies, such as all the uncertainties of using a heat pump as a heating system.

Building process. *(a) Lack of experiences of building small zero energy houses using prefabricated timber frame structures.* 14.75% of newly built housing were self-built in 2017 (Netherlands Statistics, 2020; Bossuyt, 2020). However, self-building and zero energy houses have two different markets in the Netherlands. Zero energy houses are mainly delivered by professional investors such as pension funds and housing associations (van Gastel and de Jonge, 2019; NUL20, 2020). The combination of self-building and zero energy houses is rather new in the Dutch building sector. Furthermore, the upscaling potential of self-build houses are increased because the labour costs have risen since 2015 by almost 11%. Shortage of qualified staff and increased commodity prices are the main reasons for this continuous increase (Atradius Market Monitor, 2019) (see Fig. 4).

(b) Costs of innovative zero-energy technologies. From the interviews, it appears that small changes in the energy index require large investments (from a near-zero energy house to a zero energy house). This may not be logical from the households' perspectives. Depending on the technology, the implementation of innovative zero energy technologies (e.g. insulation, heat pump, solar panels) incurs additional costs of €8k–€34k compared to conventional buildings. As the specific household income group (€36k–€45k) is still struggling to afford these

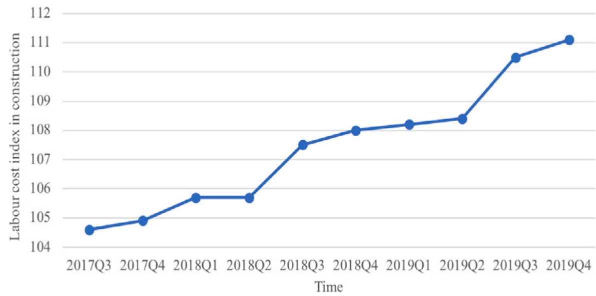

Fig. 4. Labour cost index in construction industry in the Netherlands, new residential sector- in national currency, index, 2015=100 (Eurostat, 2019).

homes given the maximum mortgage. People are more unwilling to pay the additional cost of converting homes from NZEH to ZEH. The total cost (acquisition and operating costs) might be lower in the long run, but the higher acquisition cost affects affordability to get a mortgage. *(c) Request for leave from work.* Self-builders should take at least a few months off during the building process. Also, self-builders usually underestimate the length of the construction period. *(d) Risk of dropping out of the construction process.* From the interview, the self-build process is carried out by a group of people to reduce the difficulties in the different parts of the process as well as the cost of construction. If one member leaves the group for any reason, it may affect the whole group.

4.2. Flemish scheme, as an example of a private land owner and investor

4.2.1. Business model components of Huldenberg scheme

The Huldenberg scheme is aimed at people living in a former campsite with poor living conditions. This scheme can improve the living conditions of these people by providing them with a comfortable, high quality and energy efficient house. From a social point of view, the main objective is the inclusion of the lowest income group by providing access to (near) zero energy homes. From an economic perspective, the main proposed value is to realise lower energy bills,[10] with a slight increase in rent for households (compared to their current situation where they pay rent for the property but own the caravan they live in). From an environmental perspective, the aim is to use recyclable and CO_2 low energy building materials.

The main partners of the Huldenberg scheme are the Province of Flemish Brabant and Kamp C. These two organisations are supported by the Volta organisation and the Flemish Society for Social Housing (VMSW). Kamp C,[11] a non-profit organisation and knowledge centre, is the counterpart of Urbannerdam in the Almere scheme. Volta Organisation,[12] a knowledge centre for technical and electrical installers, offers the best technological equipment packages in terms of energy performance and price, suitable for use in very small residential units. VMSW[13] provides feedback for the pilot homes (e.g. design materials, techniques) to ensure the upscaling potential of these homes by social housing associations. VMSW can make an important contribution to the development of these homes by taking the findings of this scheme into account in future designs. In addition, one and two person households are over-represented on social housing waiting lists.[14] Table 6 shows the BM of the Huldenberg scheme (see Fig. 5).

4.2.2. Institutions and industry structure

In Belgium, people mostly live in big houses in the suburbs/rural areas where they have more space to build their houses. In the Huldenberg scheme, the construction process deviates from the conventional approach to adapt to the use of prefabricated elements. Normally, an architect provides a design plan with detailed explanations of the activities on the construction site. In the Huldenberg scheme, the architect's role is limited to the design. Then a prefabrication company manufactures the prefabricated parts and assembles them on the construction site.

4.2.3. Institutional and building process barriers

Institutions. *(a) Regional/Flemish government: building regulations*. In the Flemish region, many of the social housing associations encounter inefficiencies in their financial system, as rents and construction costs are not proportional. The rent is entirely determined by the income of the households. The average rent in social housing is extremely low, around €310 per month. On the other hand, construction costs are high and even increasing rapidly, and the financial support paid by the government is not enough to cover these costs. In this way, huge amounts of money are flowing into social housing that are unsustainable in the long run.

(b) Provincial/local government: planning. Based on the land use plan for Rustenberg (the site where the houses will be built), the size of a housing unit should not be more than 50 m^2. However, based on social housing sector building standards, this size should be about 60 m^2 to provide all necessary functionalities with related minimum dimensions. Other municipalities also have such a difference in their building standards in contrast to the social housing standards.[15] Moreover, the energy rules and regulations are defined at the level of individual houses. This slows down progress in making zero energy houses by blocking collective energy solutions. For instance, installing a bigger solar panel system for a street/neighbourhood could reduce the installation and maintenance costs.

(c) Residents: culture and housing quality. During the housing subscription process, potential tenants can only apply for up to three housing projects (neighbourhood)s. When they are contacted with a concrete housing proposition, they can refuse twice before ending up at the bottom of the waiting list again. However, the quality of houses in the social market varies greatly. This causes uncertainty for potential tenants when selecting their choices since they are also not always aware of the housing quality. A more advanced system that enables faster and more flexible way of selecting housing/living options is essential to increase tenant satisfaction. In this scheme, the houses are almost identical, new-built, and all with high quality. Therefore, show casing and explaining the advantages and quality of affordable innovative nZEHs to potential tenants might reduce their resistance.

Building process. (1) Prefabrication imposes a structural change in the building process. The industry structure in Belgium is not completely ready for this change. There are some missing components in this industry such as (a) lack of experience in the social housing sector; (b) a limited number of prefabrication companies.

(2) The public tendering process for building social housing projects is not optimal. At the moment, there are no sustainable energy efficient

[10] The amount paid for monthly energy bills sometimes exceeds the low rent for social housing.

[11] https://www.kampc.be/.

[12] https://www.volta-org.be/nl.

[13] https://www.vmsw.be/.

[14] Social housing associations are independent in the choice of designs they use in their projects. So the VMSW can help them design homes that meet the standards that can be subsidised. However, they cannot make the final decision. If a social housing association decides that a design is not attractive, interesting, etc., they will not select that design. The VMSW also communicates a lot with its housing associations about new developments, innovations and interesting projects. This also makes them an important partner.

[15] In addition to this, the size of different parts of the houses have specific size regulation, for example a bedroom for X persons needs to be at least 10 m^2. These limitations restrict the design process of the houses. A potential solution can be considering a dual functionalities for particular spaces in the house.

Table 6
Business model Canvas of Huldenberg scheme.

Concept	Description
Value proposition	Ecological house because of zero carbon and circular material, cheaper houses, modular/parametric design, various packages of innovative technologies for zero energy houses, integrating with the community that currently are living there, smaller plot of land, easily disassembled, increasing thermal comfort, addressing the high demand of 1–2 person households on the waiting list for a social house, lowering the energy bills that are a lot higher than the low rents of social housing
Customer segment/ relationship	Lowest income group living in substandard housing and waiting for a social rental houses
Key partners	Private land owner, BAST architects, Inhout and Bao living company (design and supply interiors), Domus Mundi (placing recycled kitchen in larger dwellings), Volta (HVAC systems, sanitary systems, etc.), social rental agencies, province of Flemish Brabant, Kamp C (coordinator of the building project, communication between land owner and builder)
Key processes	Main processes: 1— Evaluating the existing market of nZEH (Kamp C), 2— Investigating different techniques and materials (Volta), 3— Considering the building standards of social housing (VMSW), 4— designing houses, 5— Building houses off-sites: In the pilot project, the architect and contractor Inhout BV. work together to fine-tune the construction system. 6— Buying houses by the landowner, 7— Renting the houses to the social rental agency 8— Complementary processes: – communication between actors by Kamp C, – - Advice from Volta and social rental agency – - Mentoring the residents 4— Province will collect feedback from the residents on the building and design related issues of small houses. This is an important part of the process since small houses are not common in Belgium.
Key dilemmas	– conflict between the investor and municipality due to delay in building infrastructural requirements by investors – conflict between the investor who wants a minimal investment (e.g., no PV panels, cheapest heating system and water heating system) and the pilot partners who are concerned about CO_2 and energy costs for the residents.
Key resources	Financial: province of Flemish Brabant (15 thousand euro/unit), social housing sector, Interreg project Human: start-up company, BAST architects, Inhout and Bao living company, Domus Mundi, VMSW experts, Volta experts, Kamp C experts, province of Flemish Brabant experts, Open Systems Lab UK Physical: innovative packages of technologies for building zero energy houses
Profit formula	Lower price: digitisation and standardisation Price of the house=80,000 euros (VAT)
Institutions	Friction with social housing regulations
Industry structure	New in Belgium to follow standardisation People used to live in large houses. However, the demand of small houses is increasing.

criteria (including CO_2 and circular building) and no quality assessment are performed during the public tendering process.

(3) There is a lack of experiences for designing and building small energy efficient houses. This can be due to (a) rapid growth in technological innovations and professional cannot get along this rapid growth, (b) lack of experience on innovative technology related to energy efficiency for small houses, such as heating and cooling. Sometimes, installers do not have the basic background on energy efficiency measures, such as knowing a highly insulated houses is a prerequisite of heat pump installation. The architects are used to building large houses and usually do not have the knowledge of new techniques and skills to design and efficiently equip small houses.

(4) Social housing organisations are resisting some energy efficient technologies due to the higher hassle factor compared to conventional technologies, etc. For instance, social housing organisations are hesitant to use mechanical ventilation with heat recovery due to the annual mandatory change of filter for this system.

(5) The digital platform contains predefined models for architects. This way of designing houses would not be attractive to many architects. However, some of these architects perceive it as a new market.

4.3. Co. Carlow, Kilkenny, and Wexford, as examples of public land owners and public investors

4.3.1. Business model components of three counties schemes

Table 7 presents the components of the Irish BM. The dwellings are planned to be built in three counties of Wexford, Carlow, and Kilkenny. The local authorities of these counties are involved in the project to provide provision of affordable and low carbon dwellings. These authorities are the owners with the final aim to provide the dwellings to people on social housing waiting lists. The targeted group of households is the lowest income category, mainly disabled, lone parents, elderly, and care required. The economic, social, and environmental values are similar to the Flemish scheme, such as social inclusion of low income households by providing them with more comfortable houses and using different types of low carbon materials in the construction process.

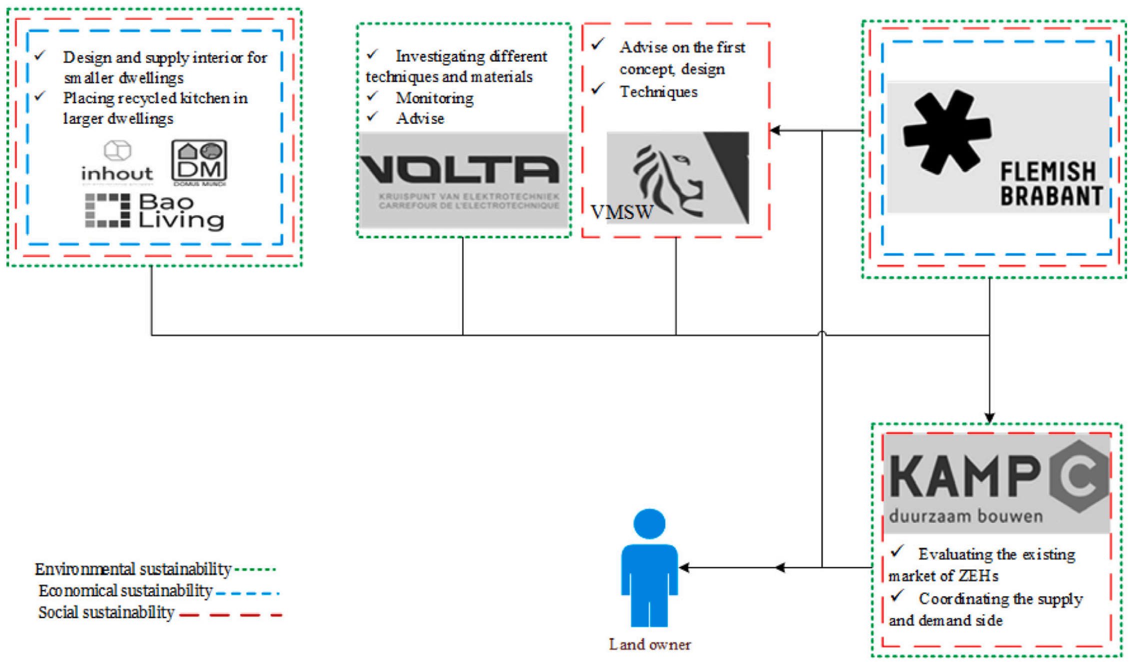

Fig. 5. Different types of sustainability values in Huldenberg scheme (green = environmental, blue = economical, red = social).

More innovative options are going to be tested in the Irish schemes in comparison to previous schemes. Standardising the building process for houses with various combination of energy efficient technologies is an essential precursor for the digital platform to meaningfully work. Once the designs, techniques, and costs and benefits of different typologies are stored on the digital platform, other individuals/entities would be able to replicate them. This will reduce the costs significantly.

The key partners are 3CEA[16] (3 Counties Energy Agency), local authorities, social housing organisations, designers, construction companies, and the "Department of Housing, Planning, & Local Government" which allocates funding to the social housing market. 3CEA helps local authorities and housing associations by identifying effective approaches to delivering ZEHs and making it attractive and sensible. Local authorities organise information evenings to those selected to be placed in a ZEH. Further training on the operations and technologies within the house takes place to ensure a smooth transfer of ownership/usage and effective operations of such. Although the local authorities, choose to build the houses on their own land, planning permissions is still required. Therefore, local authorities have to undertake all the processes in getting these permissions. Currently, the building and planning permissions have been granted in three local authorities and the processes have been completed.

The following main strategies are planned to increase the chances of a successful scale-up process: (1) demonstrating and securing positive outcomes in terms of energy savings, carbon savings, cost and efficiency for potential customers; (2) monitoring ZEHs delivered to assess uptake of the model and interaction with new social housing associations and local authorities; (3) attracting new customers through the development of an innovative financial model leading to a lean and easier to realise uptake (4) ongoing engagement with housing associations and local authorities to ensure they can retain and attract new customers in the future (see Fig. 6).

4.3.2. Industry and institutional structures

Building regulations in Ireland have been heavily negotiated and modified towards NZEB in line with the European Energy Efficiency Directive 2012. As a result, all new buildings will have to meet the A2 standard (rather than A3) from 2019. This type of regulation demonstrates the importance of upscaling ZEHs and facilitating the implementation of schemes in three counties. The big driver of new build is the new legislation in Ireland rather than a bottom-up approach of providing more energy efficient houses by owners. The main challenge is that landlords do not benefit from the energy savings from investing in renovating their homes, as tenants pay the energy bills. AI-ZEHs can provide new homes in line with regulations to people on the waiting list for social housing in Ireland.

Social housing accounts for 13% (253,000) of total housing in Ireland (Ireland Central Statistics, 2016a). The government allocated €1.1bn in 2017 to build 15,000 homes across the country. However, there were still 86,000 households on social housing waiting lists in 2018. There are two different categories of social housing in Ireland: owned by local authorities or owned by social housing organisations (Corrigan and Watson, 2018). The provision of homes by social housing organisations has increased significantly in recent years, yet local authorities provide a significant proportion of the social housing stock. In addition, in some cases in Ireland, private developers own the land and build the homes for social housing. Local authorities then buy the housing from the private developers and rent it out to social housing. This may also be a potential market for upscaling AI ZEHs. As local authorities are the main provider of social housing, the schemes were started with them. The social housing organisations provide an advisory input to improve the delivery of the schemes. Ultimately, social housing organisations will also learn from this approach and use

[16] 3CEA is a not-for-profit agency operating across three counties in the south east region of Ireland. It was established in 2002 as part of an EU sponsored programme by two local authorities and two county local development companies. Wexford was added to these counties later on to upscale the agency operation, and to achieve the ambitions in energy efficiency and renewable energy by 2030. The key focus of 3CEA is to increase awareness and promote behavioural changes to accelerate the energy transition. The agency aims to provide independent information and development of market instruments, as well as to appoint market actors to tackle energy challenges in order to achieve the low carbon targets. 3CEA connects local authorities, housing associations, and private homeowners with the required skilled personnel and subsidies available to them (European Commissions, 2015).

Table 7
Business model Canvas of the Irish Three Counties schemes.

Concept	Description
Value proposition	Financial savings to energy bills, Better air quality in the home leading to improved health, More thermally comfortable and efficient home environment, Contributing to a more sustainable environment & economy, Less dependence on fossil fuels, acting as an exemplar/ambassador for ZEHs, Quicker build homes resulting in reduced length of waiting time for assigned home
Customer segment/ relationship	Local authorities and housing associations, social housing waiting list personnel, disabled, single parents, elderly, small families (Low income), Care required personnel
Key partners	Wexford county council, Carlow county council, Kilkenny county council, social housing organisations, 3 Counties Energy Agencies (3cea)
Key processes	(a) 3CEA communicates between actors, e.g. architects, designers, energy advisers, and local authorities, (b) local authorities give building permits, plan the building processes, and provide houses to people on the waiting list
Key dilemmas	• Cultural barriers and unwillingness to change regarding the size and design of the houses
Key resources	• Financial: From local authorities, housing associations, and INTRREG project. • Human: 3CEA experts, designers, local authorities
Profit formula	• Digitisation, Combined energy efficiency measures for a group of houses, completing in-house activities as much as possible to deter external consultant costs
Institutions	• Unwillingness to change, • Not used to timber-framed structure
Industry structure	• Experienced/knowledgeable constructors' shortage

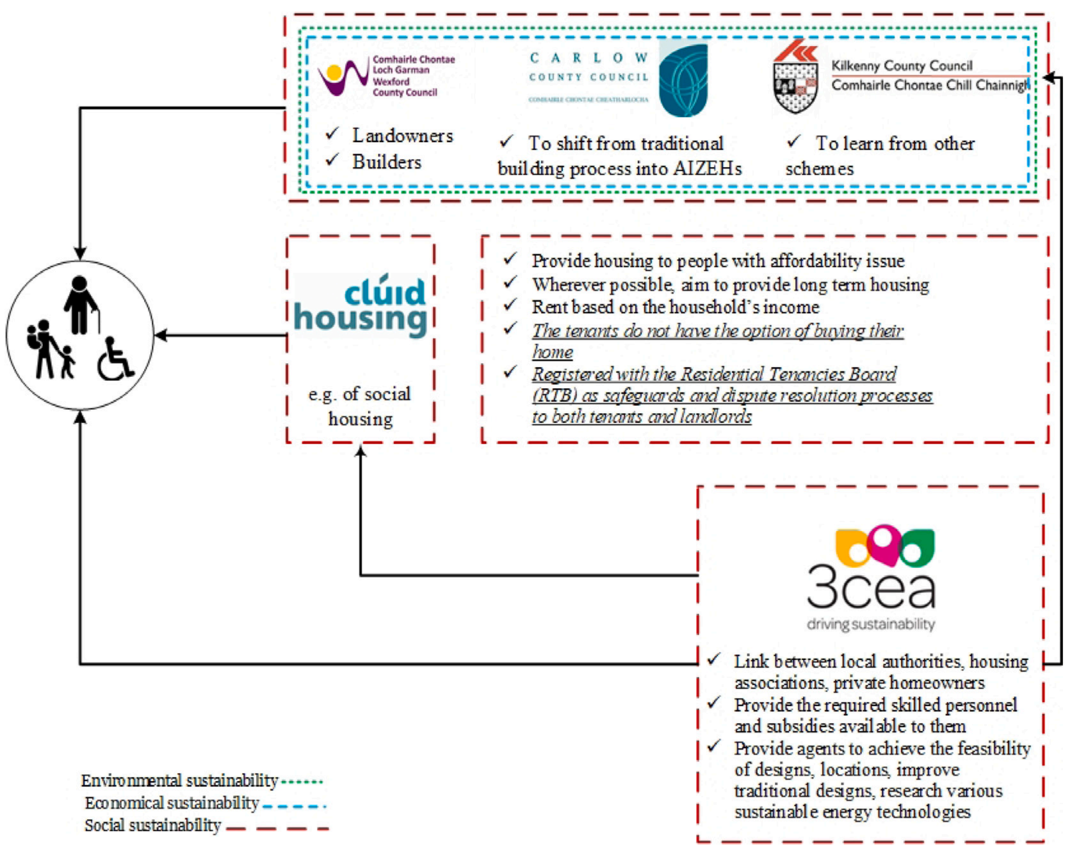

Fig. 6. Sustainability values in Ireland schemes (green = environmental, blue = economical, red = social).

it for their future projects. The three schemes in Ireland automatically act as advocates and encourage the 28 remaining local authorities and 258 social housing organisations in Ireland (Department of housing, planning, and local government, 2016, 2019; Torfs, 2019; VRT, 2019).

4.3.3. Institutional and building process barriers

Institutions. *(a) market mechanism.* Due to the economic crisis in 2009, the construction of housing almost stopped and since then the housing stock is still in crisis. The growth rate of dwellings per 1000 inhabitants was negative and amounted to −3.2% in 2016 (Ireland Central Statistics, 2016a). In addition to this, the average rent is increasing dramatically. To get a mortgage households need to have up to 20% of the total price as a deposit. Complications arise when households must pay a considerable amount to rent their current houses while saving money for a future mortgage. In order to be able to extend the H4.0E project to other housing sectors (owner-occupied and private rental sectors), the potential buyers should be able to save up the mortgage for the houses. The statistics[17] indicate a huge gap between the demand and supply side prices. To address these market failures a housing initiative with the aim of building rapid-build houses has started. However, the affordability issue still remains. The H4.0E project aims to make these houses cheaper by making the construction of these houses cheaper and using a digital platform that allows easy replication through design for manufacture and assembly.

(b) local government: planning. Local authorities occupy sufficient residential land for rapidly developing a significant amount of affordable houses. In addition, local authorities own substantial land stocks for other objectives, of which major parts can be repurposed for the residential sector. However, inadequate and unsustainable land management cause inefficient usage and volatile land prices. Long delays in planning processes and highly complicated regulations are the other hindrances at meso level (Eolas magazine, 2018; Halpin, 2018).

(c) residents: culture or housing quality. User awareness and changing user beliefs and attitudes are the main challenges in implementing AI-ZEHs. Households' resistance to change brings in more complexity in adaptation of innovative design. Irish traditional dwellings are built using concrete, and households still prefer to have a fireplace in their living rooms. The preference of households for using fireplaces also hinders the usage of a timber-framed structure. Due to these cultural hindrances, zero energy houses and efficient types of heating system cannot be easily promoted.

Building process. These barriers can be categorised into: (1) costly building design of AI-ZEHs compared to local authorities' traditional building design. Irish social housing conventionally implements identical designs of dwellings to reduce the cost of the design and make the building process faster. In contrast, new designs and techniques are needed for the H4.0E project imposing higher expenditure on the local authorities. This can be seen as a barrier in the building process. However, in the long-term and using the digital platform, this barrier is expected to diminish. Other cost components are comparable to traditional building costs. The cost of innovative technologies, such as more highly efficient boilers, is not considerably large in terms of capital investment. (2) experts and labour shortages. A more extensive explanation can be found in the institutional barriers subsection,

5. Discussion

5.1. Principles of business models in each scheme

The BMs of schemes are compared in the following lines using the principles of BMs specified by Teece (2010). (1) *End users' needs and ability to pay.* The Almere scheme aims to provide houses for lower middle/middle income groups of households by reducing the building costs. In the Flemish and Irish schemes, people on the waiting lists for social housing might get a chance to have a place to live with lower energy bills. The building costs might even reduce in the future (a) due to experimental and exploratory case studies, i.e. testing different designs, technologies, etc., (b) not yet fully achieved economies of scale, i.e. for new designs, new technologies, etc., (c) lack of resources, e.g. land in the Netherlands, skilled workers in Ireland.

(2) *Determine the manner in which enterprise delivers value.* These schemes adopt slightly different approaches in delivering value to households. 3CEA took the initiative in Ireland and proposed the scheme to the local authorities of the three counties. Irish counties and the province of Flemish Brabant will lead the building processes and distribute dwellings among households. In Belgium, the province initiated the schemes, and made a network of actors to enable successful accomplishment of the schemes. The Almere municipality supports the activities of Woningbouwatelier, e.g. land provision, and acts as a secondary partner compared to other schemes.

(3) *Persuade the end users to pay for value.* The households are the end users in the Almere scheme. In this scheme, households not only invest in building the houses, but also need to be highly motivated to build themselves. Experts predict that households in the target group might be hesitant to realise zero energy houses since their budgets, bank mortgage and savings, might not be sufficient. In the Flemish scheme, the private land owner is the end user. The land owner benefits economically from changing the purpose of the land from a recreation zone to a living space. The tenants of the houses will also benefit from living in more comfortable houses with slightly higher rent but lower energy costs. In the Irish scheme, the local authorities are the end users and own the buildings. The new Irish regulation asking for a typical Building Energy Rating (BER) of A2 or higher makes building ZEHs a priority for local authorities. At the same time, tenants benefit from lower energy bills. (4) *Required return on investment.* In all schemes, the Interreg project supports the schemes, and savings will be achieved for the tenants in the long-term by saving on energy bills.

5.2. Comparison of building costs of H4.0E schemes with similar houses and financial supports

The data for calculating the long-term cost–benefit analysis is not available, especially in terms of expected benefits, such as future bill energy savings due to more investment in energy-efficient technologies or fewer CO_2 emissions due to the more environmental friendly materials used in the construction of these homes. Therefore, a very rough comparison of the total costs and prices of these schemes are made (Table 8). For the Almere and Flemish schemes, the actual building costs are reported by the project partners. For Irish schemes, the estimated cost is used as the actual costs are not available yet. The comparison indicates that the construction costs of the houses for all projects are lower than those of similar residential houses in the regions. Fig. 7 shows increasing costs in the Netherlands and Belgium, fluctuations in Ireland and decreasing rates in construction costs in the third and fourth quarters in Ireland.

In the H4.0E project, there are no specific subsidies from the governments of these countries for owner-occupiers or tenants of these schemes. However, owner-occupiers can deduct their interest from their income, similar to other homeowners in the Netherlands. Tenants in the Flemish and Irish schemes can receive subsidies like all tenants in the countries of these schemes. In the Huldenberg scheme, a private investor receives a monthly rent of €450 and €520 from the social housing agency for four small and two larger houses, respectively.[18]

The H4.0E project also contributes financially by paying €24,300 per house for Flemish scheme. This money is used for infrastructure, equipment, architectural/engineering costs, materials, know-how and assembly/construction. As with the other schemes, the H4.0E project supports the three county schemes in Ireland. In total, each local authority can apply for bills of €88,000 for four housing units. The invoice can include costs for external expertise and services, e.g. designers and

[17] The central bank regulations limit the maximum allowable loan to 3.5 times the gross income of the applicant (Central Bank of Ireland, 2020). On the other hand, Ireland central statistics published the median gross income of households as €45k and the range of median gross income as €32K–€66K (Ireland Central Statistics, 2016b). Multiplying these incomes by 3.5 and assuming households already have 10% deposit (which first time buyers need to have), the maximum price that households can borrow from banks would be €157.5k for median gross income, and €122.5k–€231k across the range of median gross income. The average house price is equal to €256k in Ireland and the range is between €130k–€323k except for Dublin. In Dublin, the average price is between €305k–€579k (Daft.ie, 2020).

[18] As part of the normal subsidies, the Flemish government pays the investor €15,000 per house if the house is used as social housing for a minimum number of years. In addition, under the normal social housing subsidy, the Flemish government pays a rent subsidy of € 166 per household.

Table 8
Building costs and prices for the schemes in the Netherlands, Belgium (flat), Ireland (semi-detached house).

Countries	H4.0E project			Similar dwelling		
Factors	Building costs (euros/m^2)	Building costs (euros)	Price including land price (euros)	Building costs (euros/m^2)	Building costs (euros)	Price including land price (euros)
The Netherlands 50 m^2–90 m^2	1400[a]–1900[b]	95k–125k	165k–235k	2000-2500	125k–180k	195k-290k
Belgium 45 m^2–65 m^2	1400	62.5k–90k	85.5k–113k	1400-1900	85k–92k	108k–115k
Ireland	1900	125k	135k	1900-2300	105k–133k	115k–143k

[a]Plot 1 WikiHouse De Stripmaker.
[b]Plot 13 WikiHouse De Stripmaker.

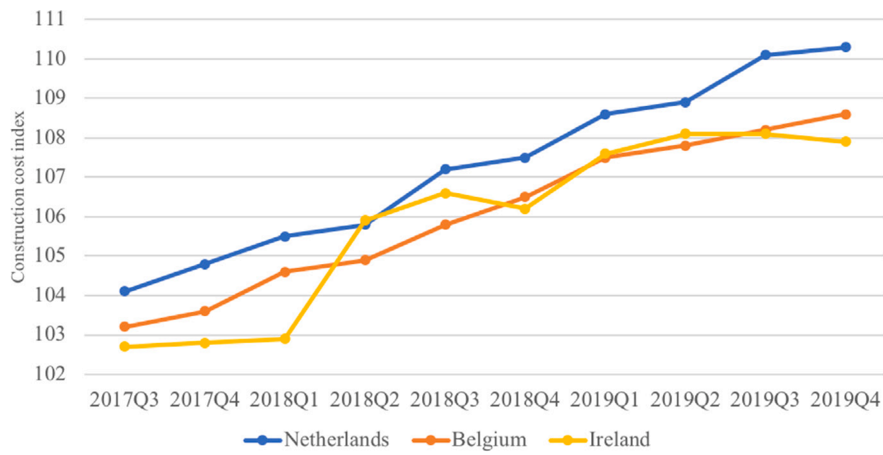

Fig. 7. Construction cost (or producer prices), new residential buildings — quarterly data (Eurostat, 2019).

architects/engineers (€4000), equipment, e.g. PV panels (€4000), and infrastructure and works, e.g. innovative construction techniques and materials (€80,000). The local authority can get 60% of these amounts funded, which equals €53,000 or €13,000 per dwelling.[19]

From the interviews, it appears that by using some kind of unified and standardised information, the labour cost of manufacturing homes can be significantly reduced because the information is provided on the digital platform and there is no need to hire a professional designer. However, the exact amount of cost savings cannot be calculated. In the case of Almere, where a very early version of the digital platform was used for the second group of households, the reduction in design costs due to the use of the digital platform was observed.

5.3. Sustainable innovations

A sustainable BM must be economically profitable while reducing environmental and socio-economic difficulties by providing socially relevant products/services (Schaltegger et al., 2016; Boons et al., 2013; Lüdeke-Freund and Dembek, 2017). Table 9 compares the social, economic and environmental values for these schemes. The environmental values of these houses are approximately equivalent in the five schemes, as these houses must comply with the new EU building regulations, i.e. near-zero energy housing. In practice, however, the energy performance needs to be investigated. The Flemish scheme contributes more to the social benefit. In the Flemish scheme, different people and institutions benefit from these houses, including private owners, people on the campsite and social housing organisations.

5.4. Upscaling potential: compatibility of industry structure and institution

Demand- and supply-side economies of scale can accelerate the development of AI-ZEHs, as stated by Shapiro and Varian (1998). The main barriers to the upscaling of AI-ZEHs are listed in Table 10. As mentioned in the introduction, the European Commission supports programmes that promote the reduction of CO_2 emissions through the use of low-carbon materials. The different models of the schemes in the Netherlands, Flanders and Ireland can serve as a showcase. Therefore, this study identified the main barriers for institutions and industry to make clear to market participants and government what is possible and to find a way to remove the barriers.

Potential upscaling of these systems could be: (1) The upscaling potential seems to be quite positive for social housing in Almere, Flanders and Ireland, as these new dwellings have advantages in terms of affordability and compliance with the near zero/zero energy building regulations. In 2019, there were 154,000 households on the waiting list in Flanders, 20,000 more than the previous year. In Ireland, the total number of households on the social housing waiting list is 86,000. This number is 5000 lower than last year, as the Irish government has allocated huge funds to “rebuild Ireland” since 2016 (Lee, 2019; Torfs, 2019). Digitisation and overcoming cultural barriers in Ireland and Belgium would offer great potential for AI-ZEHs in social housing in these two countries. The development of these houses in this sector requires high financial support from the government. This could be the drawback and raise doubts about the long run sustainability of these projects. (2) Given the high land prices and mortgage conditions, low and middle income groups may currently face financial difficulties. There are opportunities for up-zoning for (social) rental housing and more expensive owner-occupied housing. (3) Extending AI-ZEHs in the Irish and Flemish schemes to the owner-occupied sector can be a big step towards upscaling. This sector accounts for the largest share of the housing stock in these three countries (57%, 73% and 70% in the Netherlands, Belgium and Ireland respectively.) (Statista, 2019). Although the extension of AI-ZEHs of the different pilots to other target groups and other countries will increase the viability of the BMs, the country-specific institutional, technical and cultural context needs to be taken into account (see also Souaid, 2020). (4) Targeting customers who are more willing to learn about new products/services can increase the number of users of the digital platform.

[19] Almere has also received grants from the H4.0E project, but for administration and the digital platform.

Table 9
Comparison of sustainability values in Almere, Flemish, and Irish schemes.

Sustainability values	Almere scheme	Flemish scheme	Irish scheme
Economic values	– cost saving on energy bills in long-term – cheaper using digital platform in long-term, self-building,open source (reusing data) – using economies of scale: one architect – making building accessible to low skill workers	– cost saving on energy bills in long-term – pay slightly higher rents for ZEHs – Cheaper using digital platform in long-term – using economies of scale: one architect, hiring companies with mass production of prefabricated components (planned for future development)	– cost saving on energy bills in long-term – cheaper using digital platform in long-term
Social values	– lower-middle income groups building their own houses – living in a community and sharing experience/ knowledge – open source/sharing – democratise building and no need for a contractor anymore (maybe foundations)	– ZEHs for low income group of households – addressing the high demand of 1–2 person households waiting on the Flemish social rental housing – increasing the quality of life of the people in the campsite and private landowner	– ZEHs for low income group of households
Environmental values	– low carbon materials and circular timbers – using eco-friendly equipment	– Circular material	– low carbon material: timber frame and insulated concrete formwork

Table 10
Building process and institutional barriers.

Countries	Institution	Building process
The Netherlands	- For a long time, the government defined the standards and subsidies for the building industry. – The Almere municipality is more flexible compared to others – Land shortage – the absence of national legislation on shared innovative technologies, such as PV panel.	- Lack of experiences in prefabrication for small zero energy houses using timber frame structure – High value of land price, – Potential implicit costs of not working for a period – Risk of people quitting the development process
Belgium	- Grant/subsidies based on living area vs. rent based on income – Energy rules at individual housing e.g. shared solar panel: not possible – Huldenberg is flexible to change – People does not prefer identical houses and high expectation of the houses	- There is a need for educated building installers for the future development. – Architects used to large scale house – Resistance of social housing companies to balanced ventilation with heat recovery
Ireland	- hesitant to change – inadequate and unsustainable management of land – long delay in planning process by local authorities – timber-framed structure	- need for constructors – need for experiences/knowledge in construction industry due to crisis – costs of new design, techniques, and consultancy

(5) In the H4.0E project, vocational training modules are delivered which are customised for the construction industry. In these training modules, the application of low carbon materials and zero energy techniques are presented for smaller dwellings. This is a very good opportunity to motivate the suppliers and upscaling the H4.0E project. Also, the European Federation for Living (EFL) disseminates the results of the project through its European network, including European construction and real estate actors and several universities.

6. Conclusions

This study aimed to identify the characteristics of a sustainable BM for affordable innovative zero energy houses (ZEHs) in North West Europe. The main BM archetypes were identified using a bottom-up approach and data from different schemes in the Netherlands, Belgium and Ireland (three schemes). The BMs of five schemes are assessed in detail in terms of environmental, social and economic sustainability values. Regarding environmental values, the BMs of all schemes comply with EU regulations. Thus, new homes in these countries must be near-zero energy homes. However, the actual energy performance of these houses needs to be monitored and tested in the long term.

The schemes in Almere, Flanders and Ireland create social value for the target groups. The Almere programme is very important in meeting the housing needs of low-middle income households (who have little access to owner-occupied or social housing). The Flemish scheme provides social value as it benefits different groups of people and institutions, from the private sector to the lowest income households. The Irish schemes (Co.Carlow, Kilkenny and Wexford) also offer great social value by providing comfortable and energy efficient housing to the lowest income households. Of course, the Flemish and Irish governments may need to financially support ZEHs in the same way as traditional social housing. Furthermore, household participation in

Table A.11
Interviewees information.

Name	Position	Organisation/company
Ivar Diekerhof	Project leader, Almere	Woningbouwatelier
Vincent Muller	Architect/owner	Ontwerpburo MULLER
Menno Hartsema	Building cost engineer	BOUWscoop
Katja van der Valk	Process/ project manager	Building community
Gerrit de Weerd	Architect, adviser	Building community
Sarah Thiel	Adviser	Urbannerdam
Edwin Braad	Projectmanager/ Adviser	Technion
Marco Nekeman	Energy transition adviser	Invent
Katrien Tratsaert	Project leader, Flemish brabant	Province of Flemish Brabant
Sofie Torfs	Project manager	Kamp C
Piet Wielemans	Architect	Kamp C
Bart Vannoppen	Technology advisor	Volta
Emilie Verwimp	Policy officer	Flemish government
Veerle de Meulenaer	Construction engineer	Vlaamse Maatschappij junVoor Sociaal Wonen (VMSW)
Ken Dupont	Architect	Damarchitecten
Paddy Phelan	Project leader, three counties, Ireland	3CEA
Alexandra Hamilton	Senior Energy Engineer	3CEA
Shane Faulkner	Energy Engineer	3CEA
Annelies Huygen	Professor, Regulation of energy market	TNO

these projects is minimal. This could slow down the dissemination of knowledge within the community and their willingness to switch from conventional technologies to innovative sustainable technologies.

From an economic perspective, all of the above schemes add value by providing cheaper housing. Nevertheless, the social costs of the Flemish and Irish schemes (subsidies), the high prices and installation costs of new technologies, new design, etc. must be taken into account. The predicted prices and costs will decrease significantly when these new technologies are more widely deployed. In addition, the H4.0E digital platform contributes significantly to the reduction of design costs, as the original designs of the platform can be easily modified and reused instead of designing houses from scratch, and as communication between the demand and supply sides of AI-ZEH is facilitated. The Irish and Flemish schemes aim to create economic value by avoiding future energy and emissions costs in social housing, while creating better living conditions with lower energy bills for the lowest income group. Almere's scheme aims to bring low- and middle-income households into the ownership sector. Although the cost of ZEHs is lower than the cost of comparable traditional housing, the high land prices still cause affordability problems for the intended target group.

The upscaling potential of the BMs is also explored by assessing the institutional context and industry structure. For the Almere scheme, (social) rental housing and more expensive condominiums are the potential markets for future development. For the Flemish and Irish schemes there is an upscaling potential for the owner-occupied sector. In all these three countries, the small, affordable zero energy homes could be developed for both the owner-occupied and rental sectors. Of course, the country-specific context must be taken into account. Based on the interviews, various cultural barriers are identified in different schemes: design and construction material (Ireland), size (Belgium), and hesitation to change to innovative technologies (the Netherlands, Belgium). While the technical barriers can be overcome in a relatively short time, addressing the behavioural barriers requires more effort and time. The involvement of public authorities and market operators can help to remove the obstacles. In this respect, the pilot projects can be used as showcases for the development of small affordable zero energy houses.

Limitation of current study and future research. The results of the current study are limited to the available data. However, future research can further investigate the following topics (1) The current study conceptually investigated the impact of using a digital platform in the development of affordable zero energy homes. Future research can empirically investigate the costs and benefits of using a digital platform when the data are available. (2) In the current study, the Canvas Business Model was used to explain the different components of the business and the interactions between the components. The long-term cost–benefit analysis of the development of these houses was not performed as it was not the focus of this study. Moreover, the required data for this calculation was not available.

CRediT authorship contribution statement

Shima Ebrahimigharehbaghi: Conceptualisation, Methodology, Investigation, Data curation, Data analysis, Writing – original draft, Editing. **Harry van der Heijden:** Conceptualisation, Supervision, Reviewing and editing, Funding acquisition. **Marja Elsinga:** Conceptualisation, Reviewing and editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Interviewees

See Table A.11.

Appendix B. Semi-structured interview protocol: innovative business models of affordable innovative zero energy houses

(a) Pre-information

- Personal information:
- Name of the company:
- Company established by:

(b) Enterprises Information

Table B.12
Questions regarding business model components.

Components	Questions
Value proposition	What values are delivered to the customers?
Customer segment	Which group of customers does the enterprise provide the ZEH?
Customer relationship	How does the enterprise communicate with the customers?
	How does the enterprise attract new customers, keep current customers?
Key processes	What are the key activities?
	What processes are needed to deliver value?
Key resources	What resources does the enterprise have?
Profit formula	Does the company make profit?
	If yes, How does the enterprise make profit?
	What are the costs and revenues?

- What is the aim of the company?
- What is the current position at the company?
- What is the current status and size of the company?
- How do you contribute in provision of Zero Energy Housing (ZEH) in the social housing sector?

(c) Innovative Business Model
The following questions are designed using different components of Canvas BM (see Table B.12).

(d) Market Structure

- What are the main actors in the market of ZEH in the social housing sector?
- How price of a ZEH is determined in the market?
- Who are the competitors of the enterprise?

(e) Institutional Enablers and Barriers

- What kind of formal rules, regulations and procedures does the enterprise need to follow?
- What kind of policies, rules, and regulation can support the development of affordable ZEHs?
- What are the barriers?

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