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Business and Technical Concepts for Deep Energy Retrofit of Public Buildings

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ABSTRACT

Many governments worldwide are setting more stringent targets for reductions in energy use in government/public buildings. Buildings constructed more than 10 years ago account for a major share of energy used by the building stock. However, the funding and "know-how" (applied knowledge) available for owner-directed energy retrofit projects has not kept pace with new requirements. With typical retrofit projects, reduction of energy use varies between 10% and 20%, while experience from executed projects around the globe shows that energy-use reduction can exceed 50%, and renovated buildings can cost-effectively achieve the passive-house standard or even approach net zero energy status (Hermelink and Muller, 2010; NBI 2014; RICS 2013; GreenBuildingAdvisor.com 2013; Shonder and Nasseri 2015; Miller and Higgins 2015; Emmerich et al. 2011). Previous research conducted under the International Energy Agency's Energy in Buildings and Communities Program (IEA EBC) Annex 46 identified and analyzed more than 400 energy-efficiency measures that can be used when buildings are retrofitted. Measures include those related to the building envelope, mechanical and lighting systems, energy generation and distribution, and internal processes. Implementation of some individual measures (such as building envelope insulation, improved airtightness, and cogeneration) can significantly reduce building heating and cooling loads or minimize of energy waste, but require significant investments with long paybacks. However, when a limited number of core technologies are implemented together, or bundled, they can significantly reduce energy use for a smaller investment, thereby providing a faster payback.

In some countries, energy savings performance contracts (ESPC) have proven to be an effective tool for implementing energy retrofit projects. Nevertheless, in many countries the number of projects funded by ESPCs still do not form a significant part of the total investment budgeted by public institutions for energy retrofits. This paper presents the concept and several case studies that illustrate mechanisms that will increase the acceptance of deep energy retrofit (DER) and broaden acceptance of its implementation using ESPCs for a comprehensive refurbishment of existing buildings.

TECHNOLOGY BUNDLES

What Is Deep Energy Retrofit?

Though the deep energy retrofit (DER) concept is currently used all over the world, there is no established global definition of this term. Since the worldwide energy crisis of the 1970s, energy requirements pertaining to new construction and building renovation have significantly improved. Since the 1980s, building energy-use requirements in the United States have improved by more than 50%. Table 1 and Table 2 list standards and requirements used to design and construct buildings pre-1980s and today. However, buildings and building systems degrade over time. They develop cracks in the building envelope and dirty and leaky ducts, and HVAC systems are not regularly commissioned, among other problems. This results in a reduction of energy performance of at least 10%. Therefore, it is technically feasible to reduce building energy use by more than 50%, using technologies readily available on the market, by simply adapting current minimum requirements for new buildings to refurbishment of building stock.

The recently rewritten Energy Performance Building Directive (EPBD) (EU 2010), which requires buildings to "be refurbished to a nearly zero-energy condition," states that "member

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states shall not be required to set minimum energy performance requirements that are not cost-effective over a building's estimated economic life cycle." By the EPBD definition, a nearly zero-energy building (NZEB) is "a building that has a very high energy performance." In the United States, the *Massachusetts Save Energy Retrofit Builder Guide* refers to DER as "the retrofit of the building enclosure and other building systems in a way that results in a high performance building" (BSC 2013). Not many national and international bodies take their definition beyond this level of specificity except for Austria, Germany, and the Czech Republic, which decided that a high performance or "nearly zero-energy" building is a building meeting approximately the Passive House Institute standard (PHI 2015). Denmark has decided to use a new standard, defined in the Danish Building Regulations 2010 and referred to as the *2020 Definition of NZEB* (Bygningsreglementet 2010). The authors' experience shows that a significant number of commercial and public buildings have reduced their energy consumption by more than 50% after renovation, and that some have met the Passive House Institute energy efficiency standard or even net zero energy state (see examples in Figure 1). Table 3 shows some examples of United States commercial buildings (NBI 2014) in which energy use has been reduced by more than 50% from the pre-renovation baseline.

According to the Global Building Performance Network prognosis (RICS 2013), deep retrofit that follows the most recent and proposed EU guidance can improve the buildings energy performance by at least 80%.

Based on the experiences described previously, the working team of the International Energy Agency's Energy in Buildings and Communities Program (IEA EBC) Annex 61 project (IEA 2014) has decided that, for the purpose of this project, the building will be considered to achieve DER status when the site energy has been reduced by more than 50% against the prerenovation baseline with a corresponding improvement in indoor environmental quality and comfort.

Table 1. Historical Improvement of the ASHRAE Standard 90.1 (Tillou 2014)

ASHRAE Standard 90.1 Version	Energy Use Index
1975	100
1980	100
1989	86
1999	81.5
2001	82
2004	69.7
2007	65.2
2010	46.7
2013	43.4

Table 2. Historical Improvement in European National Energy Requirements for Buildings (Tillou 2014; BR10 2010; WSVO 1977)

Country	National Standard/Code	EUI, kWh/m^2	
		Pre-1980	Current
Denmark	BR10 (2010)	**Dwellings:** 53 kBtu/ft^2/yr (167.1 kWh/m^2/y)	**Dwellings:** 16,652.5 Btu/ft^2/yr + 5,631,450.0 Btu/GFA* (52.5 kWh/m^{2}y + 1650 kWh/GFA) **Office:** 22,615.6 Btu/ft^2 + 5,631,450.0 Btu/GFA (71.3 kWh/m^{2}y + 1650 kWh/GFA)
Germany	Pre-1980: WSVO (1977)	**Dwellings:** 48–79 kBtu/ft^2/y (150–250 kWh/m²/y) (IWU 2011)	**Dwellings (new):** 15,860–19,031Btu/ft^2/yr (50–60 kWh/m^{2}y)
	Current: Energy Ordinance (EnEV 2012 for new buildings)	**Schools:** 67 kBtu/ft^2/y (210 kWh/m²/y) (IWU 2011)	**Schools new/refurbished:** 49,165–39,649 Btu/ft^2/yr (125 kWh/m^{2}y)
	Refurbishment: EnEV 2009 + <30%		
Austria	OIB RL 6 (OIB 2011)	Maximum U-values	Heating energy demand:
			Residential buildings: Max. 27,754.1 Btu/ft^2/yr (87.5 kWh/m^{2}y)
			Nonresidential buildings: Max. 9516 Btu/ft^2/yr (30 kWh/m^{2}y)

* GFA = gross floor area

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Major Renovation and DER

The U.S. Department of Energy (DOE) (DOE 2010) and EPBD (EU 2010) define a major building renovation as any renovation where the cost exceeds 25% of the replacement value of the building. EPBD also defines building renovation as a major renovation if more than 25% of the surface of building envelope undergoes renovation.

Buildings usually undergo major renovation for reasons other than energy use reduction. The most common reasons include the following:

- Extension of the useful building life requiring overhaul of its structure, internal partitions, and systems
- Repurposing of the building, e.g., renovation of old warehouses into luxury apartments or into boutique shops, or renovation of old Army barracks into offices
- Bringing the building into compliance with new or updated codes
- Remediation of environmental problems (such as mold and mildew) and improvement of the visual and thermal comfort and indoor air quality
- Adding value to increase investment (for example, increasing useful space and/or space attractiveness/quality) resulting in a higher sell or lease price

It is best to time a DER to coincide with major renovations because, during renovation, the building is typically evacuated and gutted; scaffolding is installed; single-pane and damaged windows are scheduled for replacement; building envelope insulation is considered; and most mechanical, electrical lighting, and energy conversion systems (e.g., boiler and chillers), and connecting ducts, pipes, and wires will be replaced anyway.

In a major building renovation, a significant sum of money must be budgeted (programmed) to cover the cost of the construction and of the energy-related scope of the renovation, which should be designed to meet minimum energy code requirements. These funds may be applied to implement advanced energy retrofit design. The shortage of publicly appropriated funds for major renovation projects, which can slow the number and pace and their implementation as DER, can be resolved by using public-private partnership (PPP) models.

Additional funding can become available either from the government or from the private funding sources (using energy savings performance contract [ESPC] or utility energy service contract models). In some countries, such as the United States, the ESPC requires that measures linked to DER be clearly distinguished from the major renovations, which is not considered linked to reduction of energy consumption.

Technologies Used for DER and Their Cost Effectiveness

Several pilot projects have been funded in various European countries to develop best practice examples for DER. Typical measures applied in these projects usually included those used for passive houses (Table 4).

Research and analysis conducted by U.S. Army Corps of Engineers Engineer Research and Development Center (Zhivov et al. 2011) has developed major parameters for building envelop new construction and major renovation (Table 5).

Results drawn from an Annex 61 survey, combined with discussions conducted at the ASHRAE TC 7.6 Public Buildings working group meeting and with previous experience of the team, were used to generate a list of energy-efficiency technologies (Table 6). This core bundle of technologies will be used in further technical and economical analyses by simulating representative buildings in different climate zones of participating countries. Modeling will be conducted for all 17 U.S. climate zones (c.z.s) and for representative climates in Austria (c.z. 5A, 6A and 7), Canada (c.z. 4C, 5A,B,C, 6A, 7, and 8), Denmark (c.z. 5A) Estonia (c.z. 6A), Finland (c.z. 6A and 7), Germany (c.z. 5A0), Poland (c.z. 5A and 6A) and Sweden (c.z. 5A, 6A, 7, 8). The analysis assumes that energy prices in different countries range from: \$0.027 to \$0.097/kWh (gas) and \$0.08 to \$0.35/kWh (electricity).

In addition to the core bundle of technologies listed in Table 4, different building types and specific Poland climate (c.z. 5A) technologies (IEA 2009; ASHRAE 2011) can be used in the renovation project.

Some of the listed energy efficiency measures (e.g., wall-and-slab insulation, window replacement) listed in Tables 2, 3, and 4 are costly and have a long payback period when used individually. To become cost effective, DER must exploit the effects of synergy between different demand- and supply-side measures, and implement an innovative and integrative design approach. To increase a building's value and improve its indoor climate, DER must include quality assurance (QA) and quality control (QC) processes that specify the areas of major concern to be addressed and checked during the design, construction, and post-occupancy phases, and it must clearly delineate the responsibilities and qualifications of stakeholders in this process. This process addresses parameters and qualities of materials, components and building systems to be used, installation methods, testing, and commissioning. Special attention needs to be paid to architectural details to be used for the building envelope renovation, continuity of thermal and air barriers, windows and their installation techniques, and control systems. Once established, QA and QC processes, which will have a significant effect on the building performance, may be implemented at minimal cost.

Specification of a high-performance building envelope in the retrofit project can significantly reduce the size and cost of heating and cooling loads. The separation of ventilation and heating/cooling systems using a dedicated outdoor air system (DOAS) can significantly reduce the size and space (and cost) of the duct system and allow the HVAC system to be better controlled.

Specification of an advanced lighting design using a combination of electrical and daylighting, ambient and task lighting, and efficient luminaries and control strategies can significantly reduce electrical consumption by lighting and reduce the cooling load on HVAC system.

Figure 1 *Example of DER projects: (a) Renovation of the medieval Franciscan monastery in Graz, Austria—zero energy building (AEE INTEC and Nussmüller Architekten ZT GmbH 2015). (b) Renovation of a residential building in Kapfenberg, Austria—85% site energy use reduction (AEE INTEC and Nussmüller Architekten ZT GmbH 2015). (c) Renovation of VOLARM barracks at Fort Polk, Louisiana—one of 30 barracks renovated to 50% site energy use reduction.(d–e) Renovation of kindergartens in Denmark (Class 1 2014). The primary energy consumption has been reduced from 71 to 33 kBtu/ft^2/y (224 to 103 kWh/m^2/y). (f) Renovation of a school campus in Aachen, Germany. The primary energy consumption has been reduced from 76 to 25 kBtu/ft^2/y (240 to 78 kWh /m^2 year).*

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Table 3. U.S. Buildings with Energy Use Reduced by More than 50% from Prerenovation Baseline (NBI 2014)

	Name	Location	Building Type	Size, ft^2 (m^2)	% Over Baseline	Baseline, %	Measured or Estimated	Project Completion
1	Home on the Range	Billings, MT	Office	8300 (772)	79	ASHRAE 90.1-1999	Measured	2006
2	Pringle Creek Painter's Hall	Salem, OR	Office, Assembly	3600 (335)	68	Other	Measured	2009
3	Jefferson Place	Boise, ID	Office, Retail	75,000 (6975)	60	Predata	Estimated	Still in design
4	King Street Station	Seattle, WA	Transportation	60,000 (5580)	56	ASHRAE 90.1-2007	Estimated	2010
5	St. Alphonsus Regional Medical Center South Tower	Boise, ID	Health Care	412,000 (38.316)	56	CBECS	Estimated	Still in design
6	Johnson Braund Design Group	Seattle, WA	Office	8000 (744)	51	Other	Measured	Ongoing

Table 4. DER Measures—European Experience

Measure	Germany	Austria	Denmark
Wall insulation	4.7–9.4 in. (12–24 cm) 1.1–0.6 Btu/hr/ft^2°F (0.20–0.10 W/m^2 K)	6.3–7.9 in. (16–20 cm) 1.1–0.6 Btu/hr/ft^2°F (0.20– 0.10 W/m^2 K)	6–12 in. (15–30 cm)
Roof insulation	7.9– 5.7 in. (20–40 cm) 1.1–0.6 Btu/hr/ft^2°F (0.20–0.10 W/m^2 K)	7.9–15.7 in. (20–40 cm) 1.1–0.6 Btu/hr/ft^2°F (0.20– 0.10 W/m^2 K)	8–16 in. (20–40 cm)
New windows	0.14–0.19 Btu/hr/ft^2°F (0.8–1.1 W/m^2 K)	triple glazing 4.0–5.1 Btu/hr/ft^2°F (0.70–0.90 W/m^2 K)	**U-value down to:** 0.09–0.21 Btu/hr/ft^2°F (0.5–1.2 W/m^2 K)
Unheated basement ceiling insulation	2.0–7.9 in. (5–20 cm) 1.4–0.6 Btu/hr/ft^2°F (0.25–0.10 W/m^2 K)	3.9–7.9 in. (10–20 cm) 1.1– 0.6 Btu/hr/ft^2°F (0.20–0.10 W/m^2 K)	4–8 in. (10–20 cm)
Reduction of thermal bridges	Reduction as good as reasonably possible	—	**Foundation down to:** 0.9 Btu/hr/ft^2°F (0.15 W/m^2 K) **Windows down to:** 4.5–2.8 Btu/hr/ft^2°F (0.8–0.5 W/m^2 K)
Improved building envelope airtightness	n50 value = 1.0 1/h – 0.6 1/h (Low-energy buildings + Passive houses)	n50 value = 1.0 1/h – 0.6 1/h (Low-energy buildings + Passive houses)	**q(50pa):** from 4l/s/m^2 to 0.5l/s/m^2
Ventilation system heat recovery	Heat recovery rate: 65%–80%	Heat recovery rate 65 – 80%	**Fan energy used to move ventilation air down to:** 0.04–0.03 Btu/ft^3 (1.5–1.2 kJ/m^3)
Solar thermal collectors for domestic hot water	**Dwellings:** 33–54 ft^2 (3–5 m^2) 17–28 ft^3 (500–800 L) storage per residential unit, 22–32 ft^2 (2–3 m^2) per shower unit and 11–14 ft^3 (300–400 L) storage per unit	In some provinces (e.g., Styria) residential buildings are obliged to have solar thermal collector	**Dwellings:** 32.3–53.8 ft^2 (3–5 m^2)
Advanced lighting system design with daylighting controls	**Dwellings:** 108–129 ft^2 (10–12 m^2) high-efficient solar evacuated tube collector and >35 ft^3 (1000 L) storage per unit	—	Yes, with daylighting and dimming control.

Table 5. Major Parameters for Building Envelope New Construction and Renovation (Zhivov et al. 2011)

Item	Component	c.z. 1		c.z. 2		c.z. 3		c.z. 4	
		Assembly Max	**Min R-Value**	**Assembly Max**	**Min R-Value**	**Assembly Max (2)**	**Min R-Value (2)**	**Assembly Max (2)**	**Min R-Value (2)**
Roof	Insulation entirely above deck	0.029 Btu/ (hr·ft^2·°F) [1.41 W/(m^2·K)]	35 ci (hr·ft^2·°F)/Btu [6.16 ci (m^2·K)/W]	0.025 Btu/(hr·ft^2·°F [14 W/m^2·K)]	40 ci (hr·ft^2·°F)/Btu [7.04 ci (m^2·K)/W]	0.0222 Btu/ (hr·ft^2·K) [0.126 W/(m^2·K)]	45 ci (hr·ft^2·°F)/Btu [7.93ci (m^2·K)/W)]	0.0222 Btu/ (hr·ft^2·°F [0,126 W/(m^2·K)]	45 ci (hr·ft^2·°F)/Btu [7.93ci (m^2·K)/W)]
	Metal building		R-11+R-30LS (hr·ft^2·°F)/ Btu [R-1.94+R-5.28LS (m^2·K)/W]		R-25+R-11+R-11LS (hr·ft^2·°F)/Btu [R-4.4+R-1.94 R-1.94LS(m^2·K)/W]		R-13+R-13+R-28ci (hr·ft^2·°F)/Btu [R-2.29+R-2.29+R-4.93ci(m^2·K)/W]		R-13+R-13+R-28ci (hr·ft^2·°F)/Btu [R-2.29+R-2.29+ R-4.93ci(m^2·K)/W]
	Vented attic and other		38(hr·ft^2·°F)/Btu [6.7(m^2·K)/W]		49(hr·ft^2·°F)/Btu [8.63(m^2·K)/W]		60(hr·ft^2·°F)/Btu [10.57(m^2·K)/W]		60(hr·ft^2·°F)/Btu [10.57(m^2·K)/W]
Walls	Mass	0.067 Btu/ (hr·ft^2·°F) [0.38 W/(m^2·K)]	15ci (hr·ft^2·°F)/Btu [2.64ci (m^2·K)/W]	0.067 Btu/ (hr·ft^2·°F) [0.38 W/(m^2·K)]	15ci(hr·ft^2·°F)/Btu [2.64ci (m^2·K)/W]	0.05 Btu/(hr·ft^2·°F) [0.284 W/(m^2·K)]	20ci(hr·ft^2·°F)/Btu [3.52ci (m^2·K)/W]	0.04 Btu/(hr·ft^2·°F) [0.227 W/(m^2·K)]	25ci (hr·ft^2·°F)/Btu [4.4 ci (m^2·K)/W]
	Metal build-ing		R-13+R-6ci (hr·ft^2·°F)/ Btu [R-2.29+R-1.06 ci (m^2·K)/W]		R-13+R-6ci (hr·ft^2·°F)/Btu [R-2.29+R-1.06 ci (m^2·K)/W]		R-13+R-11ci (hr·ft^2·°F)/Btu [R-2.29+R-1.94ci (m^2·K)/W]		R-13+R-17ci (hr·ft^2·°F)/Btu [R-2.29+R-2.99ci (m^2·K)/W]
	Steel framed		R-13+R-7ci (hr·ft^2·°F)/ Btu [R-2.29+R-1.23 ci (m^2·K)/W]		R-13+R-7ci (hr·ft^2·°F)/Btu [R-2.29+R-1.23 ci (m^2·K)/W]		R-19+R-11ci (hr·ft^2·°F)/Btu [R-3.35+R-1.94ci (m^2·K)/W]		R-19+R-15ci (hr·ft^2·°F)/Btu [R-3.35+R-2.64ci (m^2·K)/W]
	Wood framed and other		R-13+R-4ci (hr·ft^2·°F)/ Btu [R-2.29+R-0.7 ci (m^2·K)/ W]		R-13+R-4ci (hr·ft^2·°F)/Btu [R-2.29+R-0.7 ci (m^2·K)/W]		R-13+R-8ci (hr·ft^2·°F)/Btu [R-2.29+R-1.41ci (m^2·K)/W]		R-19+R-9ci (hr·ft^2·°F)/ Btu [R-3.35+R-1.59ci (m^2·K)/W]
	Below grade/ basement	0.2 Btu/hr·ft^2·°F) [1.14 W/(m^2·K)	5 (hr·ft^2·°F)/Btu [0.88(m^2·K)/W]	0.1 Btu/ hr·ft^2·°F) [0.568 W/(m^2·K)	10 (hr·ft^2·°F)/Btu [1.78 (m^2·K)/W]	0.1 Btu/(hr·ft^2·°F) [0.568 W/(m^2·K)]	10 (hr·ft^2·°F)/Btu [1.76 (m^2·K)W]	0.067 Btu/ (hr·ft^2·°F) [0.38 W/(m^2·K)]	15(hr·ft^2·°F)/Btu [2.64(m^2·K)/W]
Floors Over Unconditioned Space	Mass	0.1 Btu/(hr·ft^2·°F) [0.57 W/(m^2·K)]	R-8 (hr·ft^2·°F)/Btu [1.41 (m^2·K)/W] spray foam	0.0416 Btu?(hr·ft^2·°F) [0.236 W/(m^2·K)]	R-16 spray foam+ R-6ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 1.06ci (m^2·K)/W]	0.0416 Btu (hr·ft^2·°F) [0.236 W/(m^2·K)]	R-16 spray foam+ R-6ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 1.06ci (m^2·K)/W]	0.033 Btu/ (hr·ft^2·°F) [0.187 W/(m^2·K)]	R-16 spray foam+ R-11ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 1.94ci (m^2·K)/W]
	Steel joist		R-8 (hr·ft^2·°F)/Btu [1.41 (m^2·K)/W] spray foam		R-16 spray foam+ R-8ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 1.41ci (m^2·K)/W]		R-16 spray foam+ R-8ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 1.41ci (m^2·K)/W]		R-16 spray foam+ R-13ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 2.29ci (m^2·K)/W]
	Wood framed and other		11(hr·ft^2·°F)/Btu [1.94(m^2·K)/W]		R-19+ R-5ci (hr·ft^2·°F)/Btu [R-3.35+ 0.88ci (m^2·K)/W]		R-19+ R-5ci (hr·ft^2·°F)/Btu [R-3.35+ 0.88ci (m^2·K)/W]		R-19+ R-10ci (hr·ft^2·°F)/Btu [R-3.35+ 1.76ci (m^2·K)/W]

Table 5. Major Parameters for Building Envelope New Construction and Renovation (Zhivov et al. 2011) ***(continued)***

Item	Component	c.z. 1		c.z. 2		c.z. 3		c.z. 4	
		Assembly Max	**Min R-Value**	**Assembly Max**	**Min R-Value**	**Assembly Max (2)**	**Min R-Value (2)**	**Assembly Max (2)**	**Min R-Value (2)**
Slab-on-Grade	Unheated	F-0.73 Btu/(hr·ft·°F) [0.22(m·K)/W]	NR	F-0.73 Btu/(hr·ft·°F) [0.22(m·K)/W]	NR	F-0.73 Btu/(hr· ft·°F) [0.22(m·K)/W]	NR	F-0.54 Btu/(hr· ft·°F) [0.16(m·K)/W]	R-10 (hr·ft^2·°F)/Btu for 24in. [R-1.76(m^2·K)/W for 60 cm]
	Heated	F-0.64 Btu/(hr·ft·°F) [0.19(m·K)/W]	R-7.5 for 12in. + R-5ci below (hr·ft^2·°F)/Btu [R-1.32 for 30cm + R-0.88 below (m^2·K)/W]	F-0.64 Btu/(hr·ft·°F) [0.19(m·K)/W]	R-7.5 for 12in. + R-5ci below (hr·ft^2·°F)/Btu [R-1.32 for 30cm + R-0.88 below (m^2·K)/W]	0.6 Btu/(hr·ft^2·°F) [3.4 W/(m^2·K)]	R-7.5 for 12in. + R-5ci below (hr·ft^2·°F)/Btu [R-1.32 for 30cm + R-0.88 below (m^2·K)/W]	F-0.54 Btu/(hr· ft·°F) [0.16(m·K)/W]	R-10 for 24in. + R-5ci below (hr·ft^2·°F)/Btu [R-1.76 for 60cm + R-0.88 below (m^2·K)/W]
Doors	Swinging	0.6 Btu/(hr·ft^2·°F) [3.4 W/(m^2·K)]	Insulated	0.6 Btu/(hr·ft2·°F) [3.4 W/(m^2·K)]	Insulated	0.6 Btu/(hr·ft^2·°F) [3.4 W/(m^2·K)]	Insulated	0.6 Btu/(hr·ft^2·°F) [3.4 W/(m^2·K)	Insulated
	Nonswinging	U-0.5 Btu/(hr·ft^2·°F) [2.84 W/(m^2·K)]	Insulated	0.35 Btu/(hr·ft^2·°F) [2.0 W/(m^2·K)	Insulated	0.5 Btu/(hr·ft^2·°F) [2.84 W/(m^2·K)]	Insulated	0.4 Btu/hr·ft^2·°F) [2.27 W/(m^2·K)]	Insulated
Vertical Glazing	Window to wall ratio (WWR)	≤20%		≤20%		≤20%		≤20%	
	Thermal transmittance (U-value)	< 0.35 Btu/(hr·ft^2·°F) [1.98W/(m^2·K)]		≤0.35 Btu/(hr· ft^2·°F) [< 1.98W/(m^2·K)]		≤0.3 Btu/(hr·ft^2·°F) [1.7 W/(m^2·K)]		≤0.3 Btu/(hr·ft^2·°F) [1.7 W/(m^2·K)]	
	Solar heat gain coefficient (SHGC)	≤0.25		≤0.25		≤0.25		≤0.35	

Table 5. Major Parameters for Building Envelope New Construction and Renovation (Zhivov et al. 2011) *(continued)*

Item	Component	c.z. 5		c.z. 6		c.z. 7		c.z. 8	
		Assembly Max (2)	Min R-Value (2)	Assembly Max (2)	Min R-Value (2)	Assembly Max (2)	Min R-Value (2)	Assembly Max (2)	Min R-Value (2)
Roof	Insulation entirely above deck	0.020 Btu/ (hr·ft^2·°F) [0.11W/(m^2·K)]	50 ci (hr·ft^2·°F)/Btu [8.81 ci (m^2·K)/W]	0.0167 Btu/ (hr·ft^2·°F) [0.095 W/(m^2·K)]	60 ci (hr·ft^2·°F)/Btu [10.57 ci (m^2·K)/W]	0.0154 Btu/ (hr·ft^2·°F) [0.307W/(m^2·K)]	65 ci (hr·ft^2·°F)/Btu [11.45 ci (m^2·K)/W]	0.0133 Btu/ (hr·ft^2·°F) [0.0755W/(m^2·K)]	75 ci (hr·ft^2·°F)/Btu [13.21 ci (m^2·K)/W]
	Metal building		R-13+R-13+R-34ci (hr·ft^2·°F)/Btu [R-2.29+R-2.29+R-5.99ci(m^2·K)/W]		R-13+R-13+R-38ci (hr·ft^2·°F)/Btu [R-2.29+R-2.29+ R-6.69ci(m^2·K)/W]		R-13+R-13+R-43ci (hr·ft^2·°F)/Btu [R-2.29+R-2.29+R-7.57ci(m^2·K)/W]		R-13+R-13+R-53ci (hr·ft^2·°F)/Btu [R-2.29+R-2.29+R-9.33ci(m^2·K)/W]
	Vented attic and other		60 (hr·ft^2·°F)/Btu [10.57ci (m^2·K)/W]		71 ci (hr·ft^2·°F)/Btu [12.50 (m^2·K)/W]		82 (hr·ft^2·°F)/Btu [14.44 (m^2·K)/W]		93 (hr·ft^2·°F)/Btu [16.38 (m^2·K)/W]
Walls	Mass	0.033 Btu/ (hr·ft^2·°F) [0.187 W/(m^2·K)]	30 ci (hr·ft^2·°F)/Btu [5.28 ci (m^2·K)/W]	0.029 Btu/ (hr·ft^2·°F) [0.165W/(m^2·K)]	35 ci (hr·ft^2·°F)/Btu [6.16 ci (m^2·K)/W]	0.025Btu/(hr·ft^2·°F) [0.142W/(m^2·K)]	40 ci (hr·ft^2·°F)/Btu [7.04 ci (m^2·K)/W]	0.020 Btu/ (hr·ft^2·°F) [0.114W/(m^2·K)]	50 ci (hr·ft^2·°F)/Btu [8.81 ci (m^2·K)/W]
	Metal building		R-19+ R-17ci (hr·ft^2·°F)/ Btu [R-3.35+ 2.99ci (m^2·K)/ W]		R-19+ R-23ci (hr·ft^2·°F)/Btu [R-3.35+ 4.05ci (m^2·K)/W]		R-19+ R-28ci (hr·ft^2·°F)/Btu [R-3.35+ 4.93ci (m^2·K)/W]		R-19+ R-38ci (hr·ft^2·°F)/Btu [R-3.35+ 6.69ci (m^2·K)/W]
	Steel framed		R-19+ R-20ci (hr·ft^2·°F)/ Btu [R-3.35+ 3.52ci (m^2·K)/ W]		R-19+ R-25ci (hr·ft^2·°F)/Btu [R-3.35+ 4.40ci (m^2·K)/W]		R-19+ R-30ci (hr·ft^2·°F)/Btu [R-3.35+ 5.28ci (m^2·K)/W]		R-19+ R-40ci (hr·ft^2·°F)/Btu [R-3.35+ 7.04ci (m^2·K)/W]
	Wood framed and other		R-19+ R-14ci (hr·ft^2·°F)/ Btu [R-3.35+ 2.46ci (m^2·K)/ W]		R-19+ R-20ci (hr·ft^2·°F)/Btu [R-3.35+ 3.52ci (m^2·K)/W]		R-19+ R-25ci (hr·ft^2·°F)/Btu [R-3.35+ 4.40ci (m^2·K)/W]		R-19+ R-35ci (hr·ft^2·°F)/Btu [R-3.35+ 6.16ci (m^2·K)/W]
	Below grade/ basement	0.067 Btu/ (hr·ft^2·°F) [0.38W/(m^2·K)]	15 ci (hr·ft^2·°F)/Btu [2.64 ci (m^2·K)/W]	0.050 Btu/ (hr·ft^2·°F) [0.284W/(m^2·K)]	20 ci (hr·ft^2·°F)/Btu [3.52 ci (m^2·K)/W]	0.040Btu/(hr·ft^2·°F) [0.227W/(m^2·K)]	25 ci (hr·ft^2·°F)/Btu [4.41 ci (m^2·K)/W]	0.028 Btu/ (hr·ft^2·°F) [0.159W/(m^2·K)]	35 ci (hr·ft^2·°F)/Btu [6.16 ci (m^2·K)/W]
Floors Over Unconditioned Space	Mass	0.033 Btu/ (hr·ft^2·°F) [0.187 W/(m^2·K)]	R-16 spray foam+ R-11ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 1.94ci (m^2·K)/W]	0.025 Btu/ (hr·ft^2·°F) [0.142W/(m^2·K)]	R-16 spray foam+ R-25ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 4.40ci (m^2·K)/W]	0.022Btu/(hr·ft^2·°F) [0.125W/(m^2·K)]	R-16 spray foam+ R-30ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 5.28ci (m^2·K)/W]	0.020 Btu/ (hr·ft^2·°F) [0.114W/(m^2·K)]	R-16 spray foam+ R-30ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 1.94ci (m^2·K)/W]
	Steel joist		R-16 spray foam+ R-13ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 2.29ci (m^2·K)/W]		R-16 spray foam+ R-25ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 4.40ci (m^2·K)/W]		R-16 spray foam+ R-30ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 1.94ci (m^2·K)/W]		R-16 spray foam+ R-35ci (hr·ft^2·°F)/Btu [R-2.82 spray foam + 6.16ci (m^2·K)/W]
	Wood framed and other		R-19+ R-10ci (hr·ft^2·°F)/ Btu [R-3.35+ 1.76ci (m^2·K)/ W]		R-19+ R-20ci (hr·ft^2·°F)/Btu [R-3.35+ 3.52ci (m^2·K)/W]		R-19+ R-25ci (hr·ft^2·°F)/Btu [R-3.35+ 4.40ci (m^2·K)/W]		R-19+ R-30ci (hr·ft^2·°F)/Btu [R-3.35+ 5.28ci (m^2·K)/W]

Table 5. Major Parameters for Building Envelope New Construction and Renovation (Zhivov et al. 2011) ***(continued)***

Item	Component	c.z. 5		c.z. 6		c.z. 7		c.z. 8	
		Assembly Max (2)	**Min R-Value (2)**	**Assembly Max (2)**	**Min R-Value (2)**	**Assembly Max (2)**	**Min R-Value (2)**	**Assembly Max (2)**	**Min R-Value (2)**
Slab-on-Grade	Unheated	F-0.54BTU/(hr·ft·°F) [0.16(m·K)/W]	R-10 (hr·ft^2·°F)/Btu for 24in. [R-1.76(m^2·K)/W for 60 cm]	F-0.52 Btu/(hr·ft·°F) [0.156(m·K)/W]	R-15 (hr·ft^2·°F)/Btu for 24in. [R-2.64(m^2·K)/W for 60 cm]	F-0.30 Btu/(hr· ft·°F) [0.09(m·K)/W]	R-15 (hr·ft^2·°F)/Btu for 24in. [R-2.64(m^2·K)/W for 60 cm]	F-0.30 Btu/(hr· ft·°F) [0.09(m·K)/W]	R-15 (hr·ft^2·°F)/Btu for 24in. [R-2.64(m^2·K)/W for 60 cm]
	Heated	F-0.44 Btu/(hr·ft·°F) [0.132(m·K)/W]	R-15 for 24in. +R-5ci below (hr·ft^2·°F)/Btu [R-2.64 for 60cm R-0.88 below (m^2·K)/W]	F-0.44 Btu/(hr·ft·°F) [0.132(m·K)/W]	R-15 for 36in. + R-5ci below (hr·ft^2·°F)/Btu [R-2.64 for 90cm + R-0.88 below (m^2·K)/W]	F-0.44 Btu/(hr· ft·°F) [0.132(m·K)/W]	R-20 for 36in. + R-5ci below (hr·ft^2·°F)/Btu [R-3.52 for 90cm + R-0.88 below (m^2·K)/W]	F-0.373 Btu/(hr· ft·°F) [0.112(m·K)/W]	R-20 for 36in. + R-5ci below (hr·ft^2·°F)/Btu [R-3.52 for 90cm + R-0.88 below (m^2·K)/W]
Doors	Swinging	0.60Btu/(hr·ft^2·°F) [3.41W/(m^2·K)]	Insulated	0.40Btu/(hr·ft^2·°F) [2.27W/(m^2·K)]	Insulated	0.40Btu/(hr·ft^2·°F) [2.27W/(m^2·K)]	Insulated	0.40Btu/(hr·ft^2·°F) [2.27W/(m^2·K)]	Insulated
	Nonswinging	0.40Btu/(hr·ft^2·°F) [2.27 W/(m^2·K)]	Insulated	0.40Btu/(hr·ft^2·°F) [2.27W/(m^2·K)]	Insulated	0.40Btu/(hr·ft^2·°F) [2.27W/(m^2·K)]	Insulated	0.40Btu/(hr·ft^2·°F) [2.27W/(m^2·K)]	Insulated
Vertical Glazing	WWR	≤20%		≤20%		≤20%		≤20%	
	Thermal transmittance (U-value)	≤ 0.27 Btu/(hr·ft^2·°F) [1.53 W/(m^2·K)]		≤ 0.24 Btu/(hr·ft^2·°F) [1.36W/(m^2·K)]		≤ 0.22 Btu/(hr·ft^2·°F) [1.25W/(m^2·K)]		≤ 0.18 Btu/(hr·ft^2·°F) [1.02W/(m^2·K)]	
	SHGC	≤0.40		NR		NR		NR	

Table 6. Proposed Core Technology Bundles for DER

Category	Name	Specification
Building envelope	Roof insulation	Level to be defined through modeling
	Wall insulation	Level to be defined through modeling
	Slab insulation	Level to be defined through modeling
	Windows	Parameters to be defined through modeling
	Doors	Parameters to be defined through modeling
	Thermal bridges remediation	See the BE Guide
	Airtightness	0.15 cfm/ft^2 @ 0.03 in. w.p. (75 Pa) (Zhivov et al. 2014) 0.6–1.0 ach @ 50 Pa
	Vapor barrier	See the Annex 61 DER guide
	Building envelope quality assurance	See the Annex 61 DER guide
Lighting and electrical systems	Lighting design, technologies, and controls	See the USACE lighting guide (USACE 2013)
	Advanced plug loads, smart power strips, and process equipment	TopTen (Europe, USA), Top Tier EnergyStar, FEMP Designated, etc.
HVAC	High performance motors, fans, furnaces, chillers, boilers, etc.	ASHRAE Standard 90.1-2013 and EPBD (Table will be provided in the guide), efficiency classification EU for motors
	DOAS	See the guide
	Heat recovery (dry and wet)	>80% efficient, see the guide
	Duct insulation	Based on EPBD requirements
	Duct airtightness	Based on EPBD requirements DIN- EN 18955 (EU 2012)
	Pipe insulation	Based on EPBD requirements DIN- EN 18955 (EU 2012)

The measures described prior result in efficient, simpler, smaller HVAC systems with smart control strategies designed to meet significantly reduced heating and cooling loads. The reduced cost of mechanical and electrical systems will compensate for a significant part of the increased construction costs resulting from the building-envelope-related measures.

The differential cost to achieve deep energy renovation compared to a standard (code-based) renovation is equal to the cost of the DER less the programmed (budgeted) cost of building renovation to meet the minimum building code discussed previously. Rough cost comparisons of different levels of building energy retrofit made by Pike Research Company are presented in Table 7 (Nock and Wheelock 2010).

BUSINESS MODELS FOR DER: CURRENT SITUATION IN EUROPE AND THE UNITED STATES

In the U.S. federal sector, the majority of ESCO projects (including those offered by the DOE, and by the U.S. Army Corps of Engineers) are implemented using indefinite delivery, indefinite quantity contracts. These contracts allow agencies of the federal government to quickly select an ESCO from a list of prequalified companies. The contracts permit ESCOs to install energy conservation measures only. Since the deep retrofit model combines building renovation with building energy efficiency measures, two separate contracts are required: a conventional, appropriations-funded contract with a renovation contractor, and a privately funded performance contract with an ESCO to implement the energy-related measures (Emmerich et al. 2010). This requires close coordination between the two contractors during the design and construction phases. In general, this approach also requires a separate entity to act as "integrator" and manager of the two contracts and contractors. Figure 2 shows the process.

Note that, in some recent projects, the U.S. General Services Agency (GSA) has achieved energy savings in excess of 60% through the use of an ESPC alone (Shonder and Nasseri 2015). GSA's approach begins with a design charrette that emphasizes the desire for deeper energy savings and the use of advanced/underused technologies. While deep energy savings have not been achieved in all cases, nevertheless in the recent National Deep Energy Retrofit project, this approach

Table 7. Energy Savings and Payback from Energy Retrofits of Various Types

Energy Retrofit Type	% Energy Savings	Simple Payback from Energy Cost Savings	Cost $/ft² (€/m²)
Retrocommissioning (mostly HVAC measures)	10 to 20	4 months to 2.4 years	0.30 (2.26)
ESCO (HVAC measures)	20 to 40	3 to 12 years **	2.50 (18.84)
DER with integrated design* (HVAC and thermal envelope)	30 to 60	7 to 12 years	2.50 (18.84)

* Includes all renovation costs including those to meet energy targets. Sources: Pike Research and LBNL

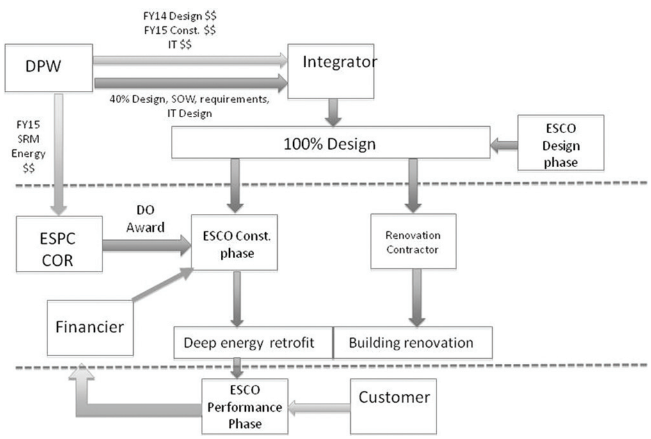

Figure 2 *Example of the business model for the U.S. federal sector.*

has allowed GSA to achieve, in the aggregate, almost twice the energy savings usually achieved in ESPC projects (Shonder and Nasseri 2015).

On the U.S. state and local level, a variety of regulations exist, and not all restrict the use of ESPC to energy conservation measures alone. In some cases, it may be possible for the ESCO to implement both the renovation and the energy retrofit project to achieve deep energy savings.

In Europe, there is no agreed framework for ESCO and general contractor collaboration. In fact, a single company can offer the solutions for both major renovations and DERs. In return, as markets are relatively small in many European Union (EU) member states, the construction sector does not necessarily have many companies that would specialize in DER, which is seen as a by-product for major construction companies, a perception that results in less competence in direct involvement into DER projects and solutions.

The fact that there is no single European business model or regulatory framework for ESPC's makes it difficult to do a comparative analysis of US and European markets. The European model offers more flexibility in that it does not require a separation of the general contractor and ESPC contractor roles. This can make the DER easier, but its total costs more difficult to define. Specifically, it becomes difficult to measure actual energy savings resulting from measures directly aiming at energy consumption reduction in isolation from other renovation measures.

Also, DERs have not become a trend in a current renovation process in European markets. The number of DERs needed to meet 2020 energy saving targets is far above the current number of DER projects. This will make it difficult to meet those targets, given that construction of new building stock has dramatically declined during the economic downturn period.

An even more worrisome aspect of the European scene is that, apart from a handful of companies that are managing the ESCO business (some of which operate in the U.S. market as well), the market does not seem to be developing. The market for DER financing is still in its infancy stages in Europe. There needs to be a significant expansion, perhaps through more elaborated PPP funding arrangements. There is a need to rapidly explore new funding sources as well as to speed up the rate of DERs to gain higher energy savings.

CASE STUDIES

Case Study 1—Germany

Project Description. The German case study is a renovation of a school campus in the municipality of Linkenheim, which was constructed in several stages between the 1960s and 1980s. The total heated gross floor area is about 177,540 ft² (16,500 m²).

- Primary school (1960s): 67,529.8 ft² (6276 m²), contains a 60 m² (646 ft²) indoor swimming pool
- Secondary school (1970s): 54,585.5 ft² (5073 m²)
- Special school for disabled persons: 18,830.0 ft² (1,750 m²)
- Gym 1(1970s): 23,026.4 ft² (2,140 m²)
- Gym 2 (1980s): 13,159.5 ft² (1,223 m²)

The reason for the DER was the school's age. One of the three heating plants, a large part of the lighting systems, and the building control system were more than 40 years old. The external wall surface of the gymnasiums required refurbishment. The targets of the DER were as follows:

- Reduction of the heating consumption by more than 50%, from which at least 70% should be provided by biomass.
- Reduction of the electricity consumption by more than 30%.
- Refurbish the thermal envelope of the gymnasiums and parts of the primary school by application of thermal insulation composite systems (extruded polystyrene) >5.9 in. (15 cm) in average.

According to German building code, the benchmarks before the DER were 57,094.2 Btu/ft^2 (180 kWh/m^{2}y) for heating and 9,515.7 Btu/ft^2 (30 kWh/m^{2}y) for electricity consumption.

The energy for heating was supplied by oil (70%) and gas (30%). Energy costs were as follows:

- Electricity: $0.00656/Btu (0.1352€/kWh)
- Gas: $0.00233/Btu (0.0481€/kWh)
- Oil: $0.00349/Btu (0.0720€/kWh)
- Wood chips: ~$0.00095/Btu (~0.0195€/kWh)

The first two years of project monitoring and verification indicate the following:

- Heating consumption was reduced by 51%
- Electricity consumption was reduced by 25%
- Annual maintenance and refurbishment costs for replaced equipment were reduced to $52,440 (46,000€).

The following measures were carried out:

- Insulation of two gymnasiums and parts of the primary school: 6.3 in. (16 cm) wall insulation, 9.4 in. (24 cm) roof top insulation and triple glazing with U-value w = 1.3
- Installation of 14,230 Btu/min (250 kW) peak photovoltaic (PV) panels and integration in the campus grid
- Installation of a 28,460 Btu/min (500 kW) biomass plant with 14,126 ft^3 (400 m^3) of wood chip storage in the former oil storage basement, a 2,846 Btu/min / 5,692 Btu/min (50 kW_{th} / 100 kW_{th}) CHP and two peak-load oil boilers with capacity of 62,612 Btu/min (1,100 kW)
- Installation of a two-pipe heating microgrid with submetering and heating stations to service all five buildings
- Installation of a building automation system
- Replacement of approximately 800 lighting systems (T8 with 39 W or 66 W per unit, T5 with 28 W or 46 W, and high-efficiency reflectors, partly with a daylight control system) with 5–7 W/m^2 (0.46–0.65 W/ft^2) in class rooms, 4 W/m^2 (0.37 W/ft^2) in floor halls, and 12 W/m^2 (1.11 W/ft^2) in gymnasiums
- Installation of ceiling heating panels with integrated lighting systems in gymnasium 1
- Refurbishment of the ventilation systems in the swimming pool, the locker and shower rooms including high-efficiency desiccant heat recovery based on the heat pump (80%)

Cost and Business Model. The municipality was able to fund all measures from appropriate funding without any bank loans, but decided to engage an ESCO within an ESPC project to carry out all measures except the building envelope measures. The economic decision-making criteria used in the public tendering process were the guaranteed saving of the ESCO, the cost to install the ECM, and the internal municipal return on investment. To separate the impacts of the ESCO measures from those of the thermal envelope, the ESCO measures were installed within 10 months, after which one heating period was monitored, and then the thermal envelope improvements were put in place.

Total costs for insulation were $2.7 million (2.4M€) (~$38/ft^2 [~290€/m^2]) with an average payback rate of 56 years.

Total costs for the ESCO measures were $2.47 million (2.2M€), or a contract life (guaranteed payback) of 14 years. Total savings were $178,980/ yr (157,000€/yr), $127,680/yr (112,000€/yr) in electricity and heating costs and $52,440/yr (46,000€/yr) in avoided maintenance costs. The M&V process has just been finalized showing that the ESCO fulfills the guaranteed savings.

Case Study 2—Austria

Project Description. The Austrian case study is a renovation of a multistory housing block in the city of Kapfenberg that was built from 1960–1961 with four floors and 24 apartments with a size of 215–699 ft^2 (20–65 m^2). The total heated gross floor area is 30,612 ft^2 (2845 m^2). The housing company was forced to do a major renovation to improve the energy, technical, and architectural quality of the building. (The apartments were too small and the equipment outdated.) The Austrian "Building of Tomorrow" research program has supported such renovation activities to break new ground for ambitious concepts (Austrian Federal Ministry of Transport, Innovation and Technology 2015).

The final energy demand (based on the calculation required for the Austrian energy certificate) of the existing building is 1,788,968,319 Btu/yr (524,163 kWh/yr), respectively 58,363 Btu/ft^2 (184 kWh/m^2) gross floor area and year.

Main targets for the renovation were the following:

- 80% energy efficiency (80% reduction of the energy demand of the existing building)
- 80% ratio of renewable energy sources (80% of the total energy consumption of the renovated building should be provided by renewable energy sources)
- 80% reduction of CO_2 emissions (80% reduction of the CO_2 emissions of the existing building)
- Plus energy standard through energy production on site (PV modules and solar thermal collectors)

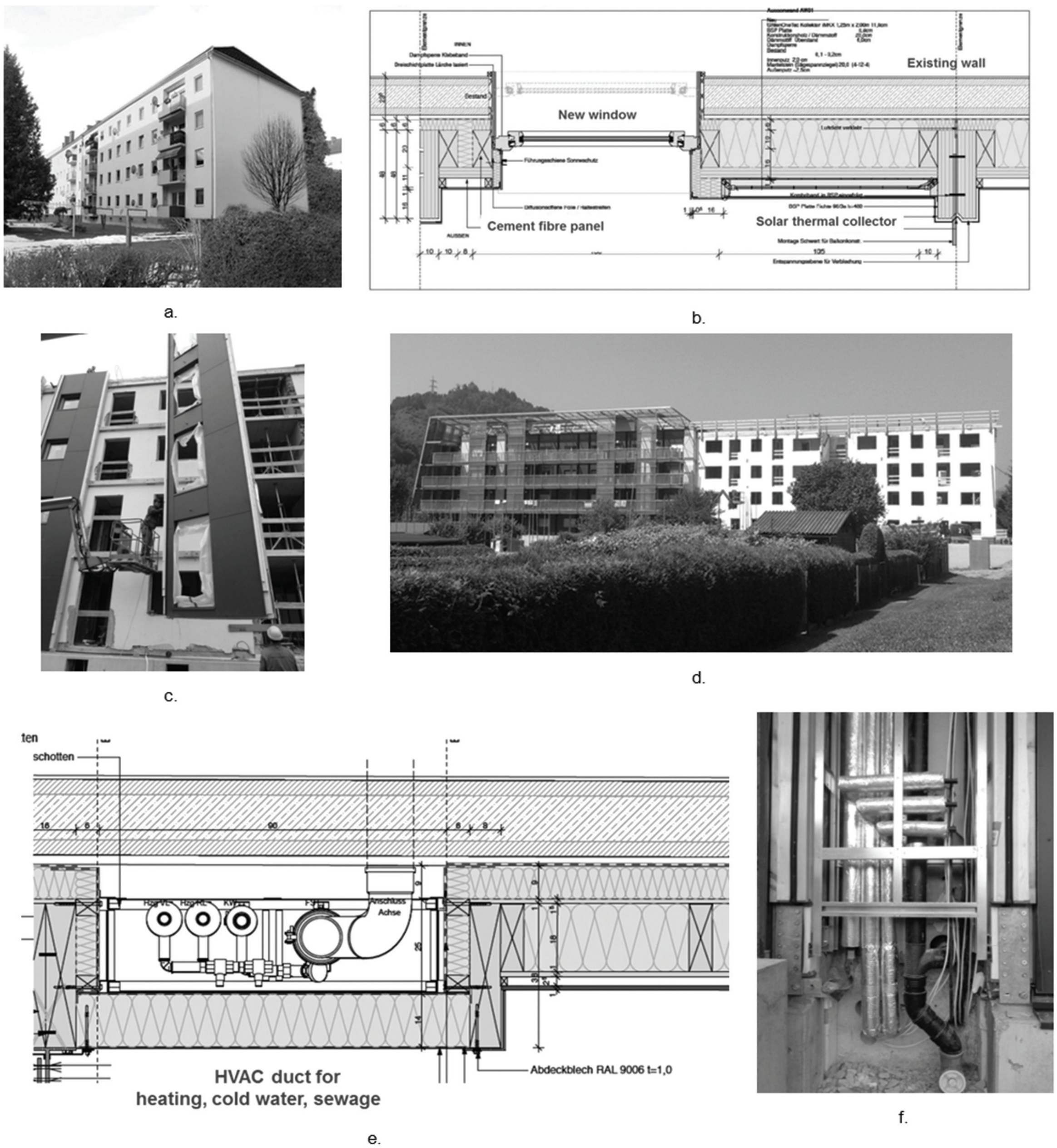

Figure 3 *Renovation of a multistory housing block in the city of Kapfenberg. (a) Picture of the building prior to renovation. (b) Schematic of the wall section with new window and solar thermal collector. (c) Mounting of façade elements. (d) Renovated façade; (e–d) Schematic and picture of new HVAC system elements installed within the external façade (AEE INTEC and Nussmüller Architekten ZT GmbH 2015).*

To demonstrate alternative (ecologically optimized) solutions to conventional thermal insulation composite systems (such as extruded polystyrene), the renovation was done using standardized, prefabricated wooden façade elements in passive house standard with integrated HVAC systems (PV, solar thermal collectors, and disposal systems). Figure 3 shows construction details of the prefabricated elements.

Energy calculations were done for five different scenarios. Figure 4 shows the results.

Energy reductions were as follows:

- Existing building—baseline
- Minimum requirements Austrian building code—reduction of 47%

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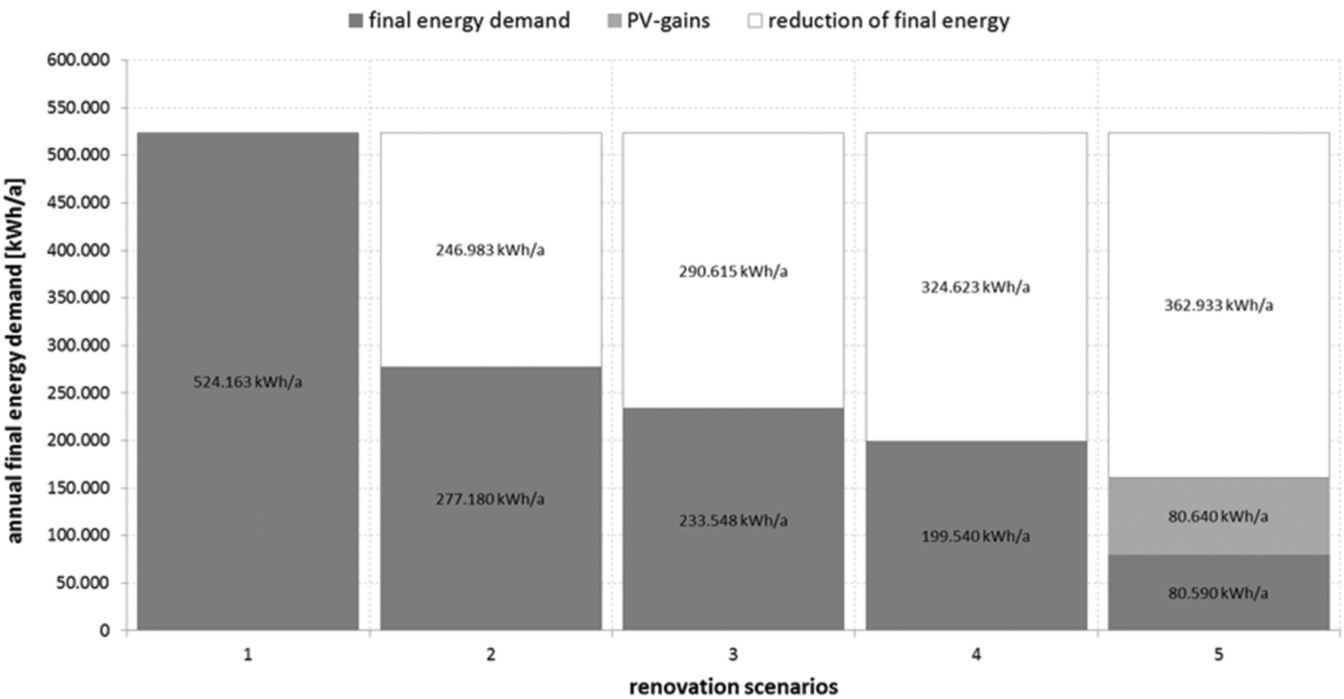

Figure 4 *Calculated energy use in different renovation scenarios.*

- Scenario e80^3 (improvement of U-values)—reduction of 55%
- Scenario 3 + mechanical ventilation with heat recovery—reduction of 62%
- Scenario 4 with PV modules and solar collectors—reduction of 85% (realized)

Energy Savings Compared to the Existing Building. The final energy demand (based on the calculation required for the Austrian energy certificate) of the renovated building is 275,053,670 Btu/yr (80,590 kWh/yr), or 8,881 Btu/ft^2/yr (28 kWh/m^2/yr). The total reduction (–1,513,914,649 Btu/yr [–443,573 kWh/yr]) is achieved by energy-efficiency measures (improvement of the building shell + ventilation with heat recovery = –1,103,876,829 Btu/yr (–323,433 kWh/yr), generation of electricity with PV-panels (–275,224,320 Btu/yr [–80,640 kWh/yr]), and generation of solar heat (–134,813,500 Btu/yr [–39,500 kWh/yr]).

Energy Savings and Costs Compared to the Baseline. In Austria, national energy targets are set for the maximum heating energy demand, and (for housing retrofit projects) for the maximum site energy demand, respectively. This energy standard compares to Scenario 5 (which realized an energy reduction of 85% compared to the existing building), and was chosen as baseline to calculate the payback period. A retrofit that follows the requirements of the Austrian Building Code (OIB 2011) commonly yields to an energy reduction of 47% as compared to the existing building. Table 8 and Table 9 further detail on the costs for energy-related measures, their energy savings, and their calculated paybacks.

The investment to improve the thermal quality of the building shell was \$0.00541/Btu/yr (16.18€/kWh/a) (annual savings); to install a ventilation system with heat recovery was \$0.00169/Btu/yr (5.05€/kWh/a) (annual savings); and to implement energy production measures was \$0.00083/Btu/yr (2.48€/kWh/a) (annual savings). The high costs for improvements to the thermal building shell in this project are unusual because DER projects do not typically include improvements to the building shell. However, this project introduced a new renovation system with prefabricated timber façade elements to the Austrian market.

Table 9 lists payback calculation results.

This retrofit achieved energy reduction of 71%, which compares well to the minimum energy requirements (47%) of the Austrian building code for retrofit. However, the innovative, prefabricated technologies used to improve the building shell yielded a payback time of 58 years. This DER project was made possible by the financial aid of the Austrian "Building of Tomorrow" research program (Austrian Federal Ministry of Transport, Innovation and Technology 2015) and the Styrian housing subsidiary program for renovation of housing projects.

Case Study 3—Denmark

Hedegaards School is located in a relatively open urban area with mainly low-rise buildings in Ballerup, Denmark. Ballerup is a municipality of approximately 50,000 inhabitants, 15 km (9.4 mi) west of Copenhagen, in an area often referred to as "greater Copenhagen." The climate in Denmark is cold-temperate. Annual mean temperature has increased from 46°F (8°C) in 1980 to 47.7°F (8.7°C) today. The number of heating degree days is 2900.The number of hours with

Table 8. Energy Savings and Investment Costs Illustrating Differences Between the Retrofit Following the Austrian Building Code and This Realized Retrofit (Project: Johann Böhm Straße, Kapfenberg, Austria).

Measures	Costs, $/ft² (€/m²)*	Total Costs	Energy Saved
Prefabricated façade elements	$28/ft² (260€/m²) facade	$433,633 (380,380€)	
Windows (triple-glazed wood windows)	$65/ft² (609€/m²) window	$245,768 (215,586€)	
Roof refurbishment (insulation)	$16/ft² (155€/m²) roof	$125,634 (110,205€)	
Improvement of the thermal quality of the building shell		$805,035 (706,171€)	148,916,016 Btu/yr (43,632 kWh/a)
Ventilation system with heat recovery		$195,647 (171,620€)	116,069,304 Btu/yr (34,008 kWh/a)
Costs for solar thermal system, including additional costs for larger storage system (with scaffolds)		$70,817 (62,120€)	130,752,030 Btu/yr (38,310 kWh/a)
PV panels (with scaffolds)		$265,324 (232,740€)	275,224,320 Btu/yr (80,640 kWh/a)
Energy production total		$336,140 (294,860€)	405,976,350 Btu/yr (118,950 kWh/a)
Total savings			670,961,670 Btu/yr (196,590 kWh/a)
		Total	Per gross floor area
Energy-related costs		124,254 $/ft² (1,172,651€/m²)	44 $/ft² (412€/m²)
Non-energy-related costs		385,759 $/ft² (3,640,609€/m²)	136 $/ft² (1,280€/m²)
Total investment costs		510,013 $/ft² (4,813,260€/m²)	179 $/ft² (1,692€/m²)

* Costs in Euros without VAT

bright sunshine is about 1700, which has also increased over the last 30 years from about 1500.

Hedegaards School is one of 10 schools in Ballerup. The school was built in 1972 and a major renovation of a portion of the school building is needed. The energy renovation of Hedegaards school was undertaken in relation to the EU School of the Future project (2015).

This case study deals with Part F of the school. These buildings are characterized by the following:

- Number of pupils: 360
- Number of adults (teachers, administration workers, etc.): 18-20
- Gross area: 41,426 ft² (3,850 m²)
- Gross volume: 282,517 ft³ (8000 m³)
- Façade surface area: ~9,684 ft² (~900 m²), of which 65% is glazed

Most of the area is located at the ground floor, and about one fourth in a high basement to the east of the building.

The floor plan shows that class rooms are placed along the perimeter of the mostly one-story building. The building interior includes corridors, an auditorium, toilets, and a few more rooms. The high basement contains a cafeteria, which is no longer in service. It future use has not yet been decided.

Before renovation, heating and electricity energy consumption and costs were as follows:

- Heating: 59,315Btu/ft²/yr at $0.00003/Btu = $65,550/yr (187 kWh/m²/yr at 0.08 €/kWh = 57500€/yr)
- Electricity: 13,005 Btu/ft²/yr at $0.00009/Btu = $46,740/yr (41 kWh/m²/yr at 0.26 €/kWh = 41000€/yr)

In general, the building needed renovation. The roof was not weathertight, the windows were leaky, and the insulation levels were generally low.

The exterior walls were of double brick construction. Between the two layers of bricks was a layer of insulation 2.75 in. (70 mm) thick. However, in several places the wall was solid (uninsulated) and thus had thick thermal bridges.

The windows were double pane, placed in a band almost all around the building (Figure 5). Many of the windows leaked and the frames were in need of paint.

The school was heated by a hydronic system with two radiators in each classroom. The radiators preheated the fresh air, which entered through the radiators. The radiators were

Table 9. Payback Calculation Results Illustrating Differences Between Retrofit Following the Austrian Building Code and This Realized Retrofit (Project: Johann Böhm Straße, Kapfenberg, Austria)

Parameter	Measure	Description
Investment costs	\$1,336,822 (1,172,651€)	
Energy Savings per year	\$19,096/yr (16,751€/a.)	= \$7,914/yr (6942€/a) electricity + \$11,182/yr (9,809 €/a) district heating)
Adequate target rate	3.75%	
Real adequate target rate	1.52%	
Inflation	2.20%	
Price rise for electricity	3.90%	Energy price electricity: \$0.10 (0.094103€) (04/24/2014)
Real price rise for electricity	1.66%	
Price rise district heating	4.80%	Energy district heating: \$0.09 (0.079865€) (04/24/2014)
Real price rise district heating	2.54%	
Simple payback time	70 years	
Internal interest rate	1.52% p.a.	
Net present value	–\$865,608.82914 (–759,306€)	
Annuity	–\$36,127.73955 (–31,691€)	
Annuity factor	0.042	
Amortization	58 years	

installed in a previous renovation project. Heating was originally provided through the ventilation system, supplemented by electrical resistance heaters in each classroom. Heat was provided from the local district heating network as high-temperature water in pressurized pipes.

The electrical lighting in the classrooms was provided by fluorescent tubes (T8) controlled by occupancy sensors. The system was relatively efficient and it would be difficult to justify replacement based on simple return on investment calculated from the cost of installing a new lighting system, offset by energy savings. However, in the corridors in the central part of the building, the system was not controlled optimally and lighting levels were quite uneven. This area was used as additional teaching space and needed an upgrade in the lighting quality and level. Maintenance (changing of tubes) could be reduced considerably and the lighting levels and uniformity may have been improved by installing a LED-based system.

Energy Renovation Measures.

The building envelope. The energy renovation will greatly reduce the thermal losses of the building envelope. An average 25 cm (10 in.) of insulation has been added on the roof so the average thickness now is 17.7 in. (45 cm). All the exterior walls and windows have been replaced. The new walls are insulated with 13.0 in. (33 cm) of mineral wool with a lambda value of 0.2 Btu/hr/ft^2°F (0.034 W/m^2 K). The new three-pane windows have frames with very low thermal transmittance.

Electrical lighting system in the corridors. The corridors needed improved electrical lighting. It was decided to upgrade the corridor lighting to classroom levels using LED down lights placed for uniform light distribution to allow the corridors to serve as extended teaching areas.

Renewable energy system. A PV system has been installed on the south facing sloping roof of one of the roof light systems of the school building. The area is 1,635.5 ft^2 (152 m^2) and the total installed power is 1,280.7 Btu/min peak power (22.5 kWp). The expected yearly production will be 6,588 Btu (22.5 MWh), corresponding to 1,840 Btu/ft^2/yr (5.8 kWh/m^2/yr).

Summary of Energy Savings. The heating and electrical energy before renovation and after implementation of the measures described above was calculated by the energy calculations program ASCOT (Cenergia 2015). The energy consumption has also been monitored over several years as a part of the municipality energy management programme. The correspondence between the monitored and calculated values was found to be reasonable. Data pertaining to monitored building energy use after the renovation are also available. The energy use data before and after renovation (Table 10) indicate primary energy savings of 66.7%.

The total energy renovation project cost was approximately \$4 million DKK or ~\$720,000.

CONCLUSIONS

Energy consumption of new buildings has been considerably reduced over the recent 40 years by more than 50% in both the United States and Europe. Now it is a time to improve the existing building stock and extensively reduce energy used in buildings by DER. This will help reduce fossil fuel use, help meet CO_2 targets, slow global climate change, and increase energy security and energy independence in energy-importing countries.

The examples and case studies presented in this paper show that DER is indeed possible and cost effective when it is combined with a major building renovation. Core technologies, which may not be cost effective when imple-

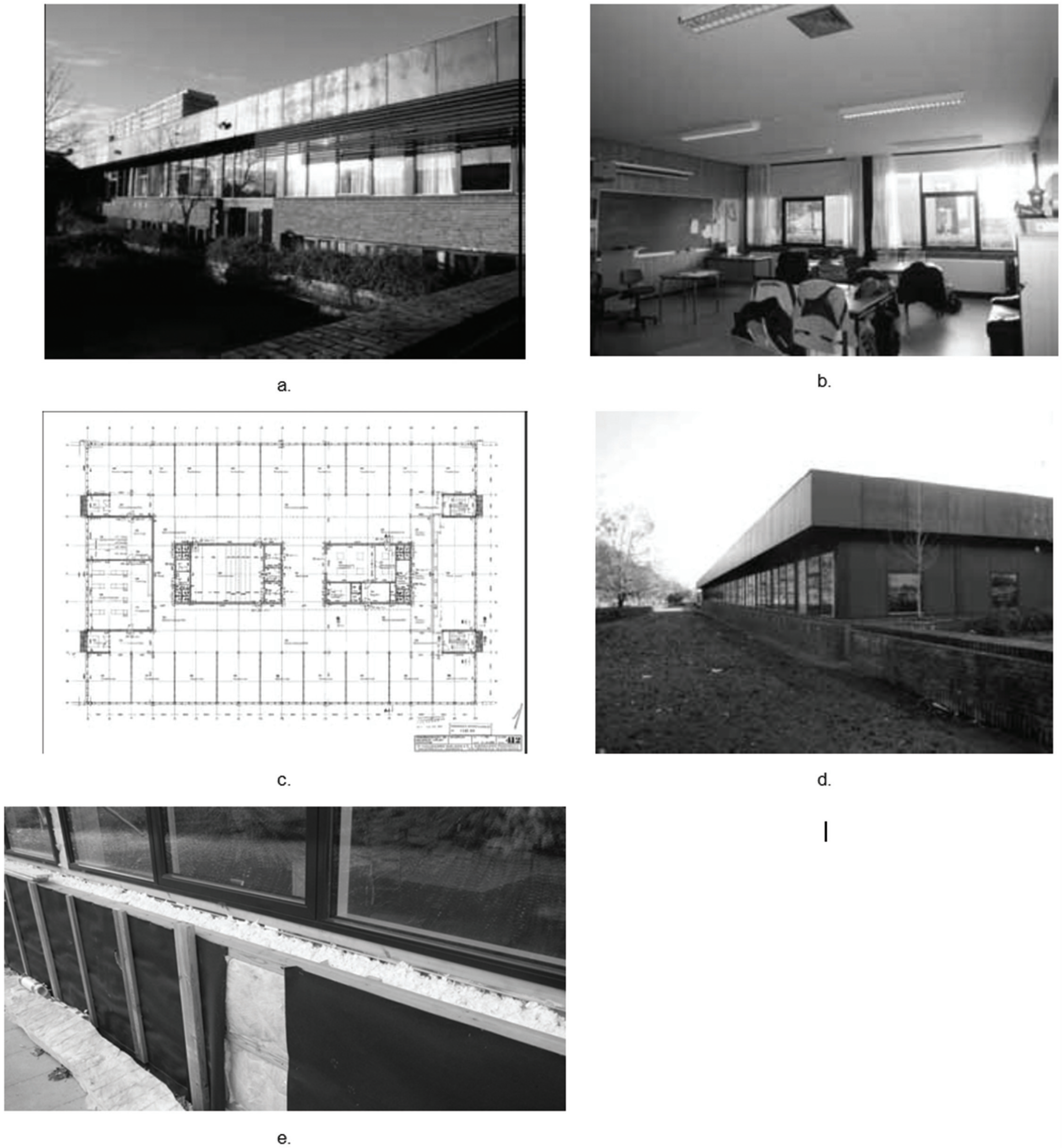

Figure 5 *Hedegaards School building. (a) South façade. (b) Classroom. (c) Floor plan. (d) Picture from WNW. (e) External insulation with the U-value as low as 0.1 W/m²K.*

mented individually, become economically attractive when implemented in technology bundles. Although the core bundled technologies required for DER remain the same, some characteristics of these technologies differ and depend on climate conditions and energy prices. The overall project cost and associated risks are further reduced by implementing an innovative and integrating building renovation design process. Also, the effectiveness and risks associated with DER significantly depend on establishing quality assurance and quality control processes that specify areas of major concern to be addressed and checked during the design, construction, and post-occupancy phases, and that define the responsibilities and qualifications of stakeholders in these processes. Implementation of major renovation projects using PPP (e.g., ESPC) can play a crucial role by increasing the number and pace of DER projects. Besides providing access to additional funding sources, PPP can contribute industry expertise during the design phase, installation, and operation and maintenance of technologies required for DER.

Table 10. Actual and Predicted Energy Consumptions after Renovation

Energy Use	Performance Before Energy Retrofit, kBtu/(hr·ft^2) (kWh/[m^2])	Performance After Renovation, kBtu/(hr·ft^2) (kWh/[m^2])	
		Calculated	Measured
Heating consumption	59 (187)	14.2 (44.7)	13.3 (41.9)
Electrical consumption	7 (22.1)	2.6 (8.2)	4.9 (15.5)
Primary energy	77.5 (242.25)	20.7 (65.2)	25.6 (80.65)
Primary energy, %	100	26.9	33.3

Despite their enormous market potential, the concepts, strategies, and business models described in this paper have not yet been fully developed and streamlined. This will be addressed during the next few years by the IEA EBC Annex 61 team. Major areas of future research include the technical and economical analysis of core bundles of technologies for three public building categories (offices, barracks/dormitories, and educational buildings) in a large number of climates, the development and demonstration of derisking strategies, and the advancement of existing funding mechanisms.

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