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Core Bundles of Technologies to Achieve Deep Energy Retrofit with Major Building Renovation Projects in Europe, the United States, and China

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ABSTRACT

Numerous pilot projects conducted all over the world have demonstrated that energy use in commercial and public buildings can been reduced by more than 50% after renovation. In fact, some renovated buildings have met the Passive House Institute energy efficiency standard or have even achieved a net zero energy state (Zhivov et al. 2015). Research (IEA 2009; ASHRAE 2015) has identified more than 400 energy efficiency measures that can be used when buildings are retrofitted. Such 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 energy waste, but require significant investments with long paybacks. However, when a limited number of core technologies are implemented together ("bundled"), they can significantly reduce energy use for a smaller investment and thereby provide a faster payback.

Characteristics of some of these core technology measures depend on the technologies available on an individual nation's market, on the minimum requirements of national standards, and on economics (as determined by a life cycle cost [LCC] analysis). In addition to these measures, requirements related to building envelope-related technologies (e.g., insulation levels, windows, vapor and water barriers, and requirements for building airtightness) depend on specific climate conditions. National teams associated with the International Energy Agency Energy Conservation in Buildings and Communities Program (IEA EBC) Annex 61, Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (EBC 2015), have studied such conditions by computer simulation (Case et al. 2016; Rose et al. 2016; Riel et al. 2016; Yao et al. 2016). This paper summarizes the results of these studies, which will be used in an IEA Energy in Buildings and Communities (EBC) Programme Annex 61, Deep Energy Retrofit—Case Studies (IEA 2015). The key to making a deep energy retrofit (DER) cost effective is to time the retrofit as part of a major building renovation that already has allocated funds, including those required to meet minimum energy requirements. Since there is an overlap between the funds allocated for the retrofit and those required for the DER, achieving the DER requires only an incremental cost because the DER is evaluated based on a bundle of core technologies, not on individual energy efficiency measures. To evaluate the cost effectiveness of DER project using bundles of core technologies, compared to a typical major building renovation based on minimum energy requirements, this paper proposes the use of net present value (NPV) of the differences in energy savings, maintenance, and insurance costs and other operational costs and revenues to estimate the budget increase limit, which makes the DER project LCC effective. Since most of parameters required for an LCC analysis differ not only by the individual country but also within the country (first costs and labor rates, energy rates, life of the project, and inflation and discount rates), the concept of scalar Ratio (McBride 1995) is used to calculate limitations in renovation budget increase.

INTRODUCTION

A list of core energy efficiency technologies (Table 1) were generated from the results of case studies of deep energy retrofits (DERs) conducted in Europe and North America (IEA 2015), surveys and discussions conducted at the ASHRAE Technical Committee (TC) 7.6 "Public Buildings" working group meetings

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Table 1. Core Technologies Bundles for Deep Energy Retrofit

Category	Name	Source for Characteristics
Building Envelope	Roof insulation	Modeling results
	Wall insulation	Modeling results
	Slab Insulation	Modeling results
	Windows	Modeling results
	Doors	National requirements
	Thermal bridges remediation	Annex 61 DER Guide (IEA 2016)
	Airtightness	The most stringent national requirements
	Vapor barrier	Annex 61 DER Guide (IEA 2016)
	Building envelope quality assurance	Annex 61 DER Guide (IEA 2016)
Lighting and Electrical Systems	Lighting design, technologies and controls	Annex 61 DER Guide (IEA 2016)
HVAC	High performance motors, fans, furnaces, chillers, boilers, etc.	The most stringent national requirements
	Dedicated outdoor air system (DOAS)	Annex 61 DER Guide (IEA 2016)
	HR (dry and wet)	The most stringent national requirements
	Duct insulation	The most stringent national requirements
	Duct airtightness	The most stringent national requirements
	Pipe insulation	The most stringent national requirements

in 2013 and 2014, and previous experience and research conducted by the Annex 61 team members (EBC 2015). These technologies, when applied together (as a bundle), will reduce the total building site energy use by about 50% (including plug loads). Technical characteristics of these building-envelop-related technologies included in the core technologies bundle have been studied through modeling and LCC analysis for representative national climate conditions. Other characteristics of these technology bundles are based on the requirements of national standards (Table 2) or on best international practices, which have been collected and summarized and will be presented in the Annex 61, *Deep Energy Retrofit Guide* (IEA 2016).

When buildings are retrofitted, additional energy efficiency measures can be used to gain greater energy savings than can be achieved by using a “core technologies bundle” alone. The use of some of these measures may depend on the end-user, rather than on contractor (e.g., purchasing and installation of more energy-efficient appliances and other plug loads and separate power lines and timers to turn-off some of electrical appliances). Other measures might include those that are specific to a particular building type (e.g., water-saving shower heads and clothes washers, which can significantly reduce domestic hot water usage) or measures specific to the project (e.g., use of low exergy heating and cooling systems: indirect evaporative cooling, radiant heating and cooling systems, and heating and cooling return water energy and other waste streams).

Building Envelope Technologies

The core bundle of technologies includes building envelope insulation levels and window characteristics optimized by the Annex 61 modeling team by computational simulation of representative buildings for different climate zones of participating countries (Case et al. 2016; Rose et al. 2016; Riel et al. 2016; Yao et al. 2016). The parameters for individual technologies were selected to enable a reduction in building site energy use of about 50% (including plug loads) and to yield a bundle that is LCC effective. Modeling was conducted for 17 US climate zones (CZs) and for representative climates in Austria, China, Denmark, Estonia, Germany, and the UK (Table 3).

The following scenarios were modeled:

- **Scenario 1.** This baseline scenario uses a pre-1980 standard to describe the building envelope and systems. Building use, systems operation schedules, and appliances and their use (expressed in W/m^2 [W/ft^2]) used in Scenario 1 were fixed for all scenarios even though in actual conditions it is likely that such scenario elements would be improved/reduced over time.
- **Scenario 2.** This “business-as-usual” (*base case*) scenario describes a major renovation with energy-related measures included in the scope of work that meet the minimum current standards (usually related to energy efficiency of fans, motors, chillers, furnaces, lighting fixtures, etc.) listed in

Table 2. Current National Standards for Renovation Projects

Country	Building Energy	Building Envelope	HVAC	Lighting
Austria	OIB Directive Nr. 6	OIB RL 6, 2011	EN 1507, EN 12237 ÖNORM H 5057, OIB RL 6, 2011	EN 12464-1 and -2 EN 15193
China	GB 50189-2015	GB 50189-2015, GB/T 7016-2008	GB 50736-2012, GB 50189-2015	GB 50034-2013 GB 50189-2015
Denmark	Danish Building Regulation 2010 DS Standard 418	Danish Building Regulation 2010	Standard 447, Standard 452	DS/EN ISO 12464-1
Estonia	Ordinance No. 63. RT I, 18.10.2012, 1, 2012; Ordinance No. 68. RT I, 05.09.2012, 4, 2012	EVS-EN ISO 10077, EVS-EN 1026 EVS-EN 12207 EVS-EN 12208	EVS-EN 13779; EN 12237; Ordinance No. 70. RT I, 09.11.2012, 12	Ordinance No. 70. RT I, 09.11.2012, 12
Germany	DIN 18599-1; EnEV 2014	EnEV 2014, DIN 18361 DIN 18355, DIN V 18599/2 DIN 4102, DIN 4108 DIN EN 13162, DIN EN 13163 DIN EN 13164, DIN EN 13165 DIN EN 13167, DIN EN 13171	EnEV 2014, DIN V 18599, DIN 1946-6, DIN EN 13779, DIN 24192 II/III/IV, DIN 4108-6, DIN 4701-10	DIN 18599-4, DIN 5035 T 1-14
Latvia	Law on the Energy Performance of Buildings, Cabinet Regulation No. 348, Cabinet Regulation No. 383, Cabinet Regulation No. 382	Latvian Construction Standard LBN 002-01	Latvian Construction Standard LBN 231-03, Latvian Construction Standard LBN 003-01	Cabinet Regulation No. 359
UK	BS EN 15603:2008	Building Regulations 2010—Conservation of Fuel and Power: Part L, Scottish Building Standards 2015—Technical Handbook 2015	Non-Domestic Building Services Compliance Guide: 2013, Non-Domestic Building Services Compliance Guide for Scotland: 2015, BS EN 15727:2010, BS 5422:2009	BS EN 12464-1: 2011, Non-Domestic Building Services Compliance Guide: 2013, Non-Domestic Building Services Compliance Guide for Scotland: 2015
USA	ANSI/ASHRAE/IES Standard 90.1-2010 ANSI/ASHRAE/IES Standard 100-2015	ANSI/ASHRAE/IES Standard 90.1-2013	ANSI/ASHRAE/IES Standard 90.1 2010	ANSI/ASHRAE/IES Standard 90.1; IESNA Recommended Practices, 10th Edition, 2010

Table 3. Representative US Department of Energy (DOE) Climate Zones in the Annex 61 Participating Countries

Country	Climate Zone(s)	Representative City
Austria	4a and 7	Wien, Obertauren
China	2a, 3a, 3c, 4a, 7	Guangzhou, Shanghai, Kunming Beijing, Harbin
Denmark	5a	Copenhagen
Estonia	6a	Tartu
Germany	5a	Wurzburg
Latvia	6a	Riga
UK	4a, 5a	London, Aberdeen
USA	1a–8b	Miami, Houston, Phoenix, Memphis, El Paso, San Francisco, Baltimore, Albuquerque, Seattle, Chicago, Colorado Springs, Burlington, Helena, Duluth, Fairbanks

Table 2. Building use schedules and plug-loads remain the same as in Scenario 1.

- **Scenario 3.** In this scenario, the characteristics of the core technology bundle listed in Table 1 are optimized to achieve about 50% of energy use reduction against the baseline or current national minimum building energy use requirement for existing buildings (whichever is more stringent).
- **Scenario 4.** This scenario optimizes the characteristics of the core technology bundle listed in Table 1 and uses additional energy efficiency measures (e.g., reduction in plug loads and domestic hot water use) to achieve the current "national dream" energy use intensity (EUI) levels in renovated buildings (e.g., the Passive House Standard) required in national regulations if life-cycle cost is effective.

Based on the results of these studies (Case et al. 2016; Rose et al. 2016; Riel et al. 2016; Yao et al. 2016), the levels of the building envelope insulation and window types required to achieve DER in different climate conditions (summarized in Tables 4 through Table 6) were identified. These values were selected based on the performance of technology bundles (not on the economics of individual measures) for different climate conditions and individual country energy prices and on minimum national requirements for these technologies. These values are therefore equal to or more stringent than those listed in Table 2. For example, insulation values of building envelope elements, characteristics of windows and requirements to airtightness presented in Tables 4 through Table 6 for the United States are more stringent than those listed in ASHRAE Standard 90.1 (2013), ASHRAE Standard 189.1 (2013), or the ASHRAE Advanced Energy Design Guides; they are not, however, as aggressive as those based on the Passive House Institute Standard (Zhivov et al. 2011; Bastian et al. 2012).

Windows

Windows allow daylight into the building and give occupants visual contact with their surroundings. They protect against the outdoor climate and transmit solar energy that can reduce energy consumption in winter. However, windows are also the least insulated part of the building thermal envelope. Older windows commonly have single-pane glass, frames that are rotten or damaged or that have thermal bridges, cracked glass, nonfunctioning locks, and/or leaky, poorly fitting sashes. Replacing such windows can not only substantially improve visual and thermal comfort but can represent an important opportunity for energy savings that, in turn, can help reduce the size of heating and cooling loads imposed on heating, ventilating, and air-conditioning (HVAC) equipment.

Determining the window options considered to be energy efficient depends on climate. In cold climates, a window's ability to retain heat inside the building is most important; in warm climates, a window's capacity to block heat gain from the sun and infiltration is a priority. The main energy parameters of a window are its insulation value, transparency to solar radiation, and airtightness. The most significant factors to consider in selecting window systems are U-factor, solar heat gain coefficient (SHGC), and visible transmittance (VT) of light. In addition, air leakage (AL) of a window assembly is a critical measure of the airtightness of the installed window system. Airtightness is usually measured in cubic meters (cubic feet) per minute of air leakage for a given framed area of the window at a specific pressure difference. Air leakage is usually expressed as $m^3/min/m^2$ ($ft^3/min/ft^2$). Table 6 lists window characteristic determined in modeling studies that are based on the climate-specific considerations (i.e., a low SHGC for warm climates and a low U-factor for cold climates).

Modern window technologies are mature and ready for use. Assuming a ten-year payback threshold, it is generally justifiable in all climate zones to undertake energy conservation projects to replace existing windows with currently available advanced windows. For major building renovation projects or projects initiated to replace failed or failing windows, the cost of base case replacement windows and the labor to install them can be considered as a budgeted "regular maintenance" cost. In such cases, premium quality replacement windows options are available for each climate zone that satisfies the ten-year payback criteria (IEA 2014). It is not only important to select windows with climate appropriate characteristics, but also to install them without creating thermal bridges with a surrounding wall (Vazquez 2016).

Table 4. Wall Insulation

Country	U-Factor, W/(m²·K) (Btu/[h·ft²·°F])	R-Value, (m²·K)/W ([h·ft²·°F]/Btu)
Austria (CZ 5A)	0.135 (0.024)	7.4. (42)
CZ 7	0.24 (0.043)	4.17 (23)
China CZ 7	0.31 (0.054)	3.2 (19)
CZ 4A	0.48 (0.084)	2.1 (12)
CZ 3A	0.60 (0.106)	1.7 (9)
CZ 2A	0.96 (0.169)	1.0 (6)
CZ 3C	0.96 (0.169)	1.0 (6)
Denmark (CZ 5A)	0.15 (0.026)	6.7 (38)
Estonia (CZ 6A)	0.17 (0.03)	5.9 (33)
Germany (CZ 5A)	0.17 (0.03)	5.9 (–33)
Latvia (CZ 6A)	0.19 (0.033)	5.3 (30)
UK (CZ 4A)	0.22 (0.039)	4.5 (26)
5A	0.22 (0.039)	4.5 (26)
US CZ 1	0.76 (0.133)	1.3 (8)
CZ 2	0.38 (0.067)	2.6. (15)
CZ 3	0.28 (0.050)	3.6 (20)
CZ 4	0.23 (0.040)	4.3 (25)
CZ 5	0.19 (0.033)	5.3. (30)
CZ 6	0.14 (0.025)	7.1. (40)
CZ 7	0.11 (0.020)	9.1 (50)
CZ 8	0.11 (0.020)	9.1 (50)

Table 5. Roof Insulation

Country	Climate Zone	U-Factor, W/(m²·K) (Btu/[h·ft²·°F])	R-Value, (m²·K)/W ([h·ft²·°F]/Btu)
Austria	4a	0.159 (0.028)	6.3 (36)
	7	0.23 (0.041)	4.4 (25)
China	2a	0.53 (0.093)	1.9 (11)
	3a	0.53 (0.093)	1.9 (11)
	3c	0.53 (0.093)	1.9 (11)
	4a	0.38 (0.067)	2.6 (15)
	7	0.30 (0.053)	3.3 (19)
Denmark	5a	0.10 (0.018)	1 (57)
Estonia	6a	0.11 (0.02)	9.1 (52)
Germany	5a	0.14 (0.025)	–7.1 (40)
Latvia	6a	0.16 (0.029)	6.3 (35)
UK	4a	0.13 (0.023)	7.7 (44)
	5a	0.13 (0.023)	7.7 (44)
USA	1	0.16 (0.029)	6.3 (35)
	2	0.14 (0.025)	7.1 (40)
	3	0.12 (0.022)	8.3 (45)
	4	0.12 (0.022)	8.3 (45)
	5	0.11 (0.020)	9.1 (50)
	6	0.09 (0.0167)	11.1 (60)
	7	0.09 (0.0154)	11.1 (65)
	8	0.08 (0.0133)	12.5 (75)

Table 6. Window Characteristics

Country	U-Factor, W/(m²·K) (Btu/[h·ft²·°F])	R-Value, (m²·K)/W ([h·ft²·°F]/Btu)	SHGC
Austria (CZ 5A)	1.09 (0.19)	0.92 (5.3)	0.60
CZ 7	1.09 (0.19)	0.92 (5.3)	0.60
China			
CZ 2A	2.55 (0.45)	0.39 (2.2)	0.48
CZ 3a	2.55 (0.45)	0.39 (2.2)	0.48
CZ3C	2.70 (0.48)	0.37 (2.1)	0.48
CZ 4A	1.79 (0.32)	0.56 (3.1)	0.68
CZ 7	1.79 (0.32)	0.56 (3.1)	0.68
Denmark (CZ 5A)	1.2 (0.21)	0.83 (4.8)	0.63
Estonia (CZ 6A)	1.1 (0.19)	0.91 (5.3)	0.56
Germany (CZ 5A)	–1.3 (–0.23)	0.77 (4.3)	0.55
Latvia (CZ 6A)	1.2 (0.21)	0.83 (4.8)	0.43
UK (CZ 4A)	1.32 (0.23)	0.76 (4.3)	0.48
CZ 5A	1.79 (0.32)	0.56 (3.1)	0.68
USA CZ 1 and 2	1.98 (< 0.35)	> 0.51 (2.9)	< 0.25
CZ 3 and 4	1.70 (< 0.30)	> 0.59 (3.3)	0.30–0.35
CZ 5	1.53 (< 0.27)	> 0.65 (3.7)	0.35–0.40
CZ 6	1.36 (< 0.24)	> 0.74 (4.2)	>50
CZ 7	1.25 (< 0.22)	> 0.80 (4.5)	>50
CZ 8	1.02 (< 0.18)	> 0.98 (5.6)	>50

Thermal Bridges

A thermal bridge is a highly conductive material that bypasses the building's insulation layer; if not addressed during DER, the thermal bridge will significantly reduce the reduction in overall energy use expected from building envelope insulation and installation of high-performance windows. The total impact of thermal bridges on the need for heating energy is generally considerable and can be as high as 30%. The impact on the cooling energy need is significantly lower.

Thermal bridges can occur at various locations of the building envelope. Thermal bridges can be categorized as follows:

- Repeating thermal bridges within a construction element (structure or frame constructions), which are included in the overall thermal transmission or U-factor calculation of the element.
- Thermal bridges at corners and junctions, including windows and doors, wall/roof junctures, and wall/wall corners. The linear thermal transmittance psi value (ψ) of these thermal bridges would be multiplied by the length over which it occurs to get the heat loss per degree Fahrenheit (Celsius); this value, multiplied by the length of the thermal bridge, would then be added to the building heat losses.
- Isolated thermal bridges, occur for example, when a steel beam penetrates a wall/roof/floor (e.g., balconies penetrating insulation layers). The point thermal transmittance is characterized by the chi value χ.

Additional transmission losses due to thermal bridges lead to a higher heating/cooling energy need and use, lower inner surface temperatures, and possibly moisture and mold problems. Their effect is especially important in the so-called "low energy" or "high-performance" buildings.

For more information on thermal bridges and their mitigation with DER projects, see Lawton (2012), ISO (1995), Erhorn-Kluttig and Erhorn (2009), and Schild (2010). Issues related to thermal bridges in European countries are discussed in Citterio et al. (2008). Most Northern and Central European countries deal with the problem in new construction. However, this is not the case in renovation projects. Specific attention has been given to collecting information on simplified approaches such as those used in Northern and Southern Europe. Only Finland applies special assessment methods (dependent on the λ ratio, i.e., the highest divided by the lowest thermal conductivity values of two adjacent layers).

There are many methods to deal with the maximum value for thermal bridges in national standards. In Germany, mitigation of thermal bridges must be designed to minimize annual heating needs using economically justifiable measures. The easiest, but less accurate method of calculating the effect of thermal bridges is to evaluate the average increase in a U-factor. The most accurate way is to calculate ψ-values for all thermal bridges and their length. In Denmark and the Czech Republic, a ψ_{max} value is set depending on the type of joint. In France, the ψ_{max} depends on the type of building. In Austria, there are no specific requirements on linear thermal transmittance ψ and point thermal transmittance χ, but the Austrian standard ÖNORM B 8110-2 includes requirements related to thermal bridges to the internal surfaces temperature factor in relation to moisture safety and condensation prevention. In North America, there are no legal requirements pertaining to thermal bridges. However, several guides based on recent research address the impact of thermal bridges on building envelope performance and provide guidance for mitigation of thermal bridges (Morrison Hershfield 2014; Pagan-Vazquez et al. 2015.)

The Annex 61, *Deep Energy Retrofit Guide* (IEA 2016) currently under development includes recommendations for the mitigation of thermal bridges and contains a catalogue of supporting architectural details for typical situations.

Improved Building Airtightness

Uncontrolled air transfer through enclosures markedly increases the energy required to heat, cool, control humidity, and regulate indoor climate conditions in buildings. Investigations into building enclosure problems indicate that air leakage is a leading cause of moisture problems (Anis 2001; Zhivov et al. 2014). These problems include mold, moisture penetration, and durability problems, especially in intersections between exterior walls, roofs, and windows; excessive rain penetration into wall cavities; unstable indoor temperature; and humidity profiles. To achieve required comfort levels, additional investments and life-cycle costs for heating and air conditioning are necessary. In many cases, buildings with insufficient airtightness may suffer from moisture-related construction failures and losses of equity values. In colder climates, air leakage problems can cause such problems as icicles on exterior facades, spalling of masonry, premature corrosion of metal parts in exterior walls, high wood moisture content, and rot. In hot humid climates, infiltrating air in combination with insufficient construction thermal bridges causes mold due to condensation on cold air-conditioned surfaces. Sealing penetrations and reducing the chimney effect of interior ventilation can address these concerns. Application of air barrier theory in a building design requires the selection of a component or layer in an assembly to serve as the airtight layer. It is important to clearly identify all air barrier components of each envelope assembly on construction documents and detail the joints, interconnections, and penetrations of the air barrier components (Anis 2001).

The air barrier material, which must be structurally supported to withstand the maximum positive and negative air pressures to which it will be exposed, may have only a limited air permeance. Existing buildings undergoing major renovations, especially those located in cold or hot and humid climates, should be sealed to the same standard as new construction if construction details allow for this. The quality assurance of that process will require a blower-door test.

For typical buildings, increasing building airtightness can easily account for 10% to 40% of the total energy saving, depending on climate. Table 7 lists requirements for building airtightness, which differ in different countries (IEA 2014) and which are used in core technology bundles.

LIGHTING SYSTEMS

Lighting accounts for almost 32% of the energy used in commercial buildings. Related energy codes are becoming more rigorous as the need to reduce energy consumption increases. Since reduction in lighting energy consumption can significantly affect a building's energy performance, lighting is a practical target. Many lighting solutions are simple and easy to implement, while others more complex; many can yield substantial results. Advanced lighting systems should be considered in all renovation projects of federal and public facilities. Table 8 lists current minimum national standards for lighting systems.

A number of lighting technologies have been available for decades, but were not often implemented in federal and public facilities due to either budgetary constraints, lack of guidance, undocumented results, or other application issues. Other technologies in the lighting field are emerging with potential for even greater energy savings if used in the right applications.

When considering energy retrofits, the following basic principles should be considered:

- Cornerstone design strategies:
  - Provide appropriate illuminance levels without overlighting.
  - Use efficient lamps, ballasts, and luminaires.
  - Reduce electric lighting usage with controls.
- Energy-saving lighting design tactics that help create visually comfortable, effective, and efficient lighted environments:
  - Optimize architecture to provide daylight in frequently occupied spaces.
  - Apply light-colored (high-reflectance) surface finishes.
  - Cluster similar tasks to improve lighting system energy efficiency.
  - Locate luminaires close to tasks that require higher illuminance.
  - Use linear fluorescent and light emitting diode (LED) luminaires predominately.
  - Use high-efficiency ballasts with appropriate ballast factors.

Table 7. Airtightness Best Practice Requirements

Country	Source	Requirement	cfm/ft² @ 75Pa*
Estonia	Ordinance No. 58. RT I, 09.06.2015, 21, 2015	6 $m^3/(h·m^2)$ @ 50 Pa for renovation 3 $m^3/(h·m^2)$ @ 50 Pa for new construction	0.42 0.21
Austria	OIB RL 6, 2011 for buildings with mechanical ventilation	1.5 1/h at 50 Pa	0.28
Denmark	Danish Building Regulations BR10 (Building Regulations 2010)	1.5 1/h at 50 Pa	0.28
Germany	DIN 4108-2	1.5 1/h at 50 Pa	0.28
US	USACE ECB for all buildings (USACE 2012), ANSI/ASHRAE/IES/USGBC Standard 189.1-2011, 2013 Supplement, ANSI/ASHRAE/IES/USGBC Standard 189.1–2013 Supplement, ANSI/ASHRAE/IES Standard 90.1-2013		0.25
	USACE HP Buildings and DER proposed requirement		0.15
Latvia	Latvian Construction Standard LBN 002-01 for buildings with mechanical ventilation	2 $m^3/(m^2h)$ at 50 Pa	0.14
UK	ATTMA-TSL2	2 $m^3/h/m^2$ at 50 Pa	0.14
CAN	R-2000	1 in.² equivalent leakage area (EqLA) @10 Pa /100 ft²	0.13
Germany	Passive House Standard	0.6 1/h at 50 Pa	0.11

*Based on example for four-story building, 36.6 × 33.5 m (120 × 110 ft), n = 0.65. (Zhivov et al. 2014).

Table 8. International Requirements and Standards for Lighting Systems

Country	Standards and Requirements
Austria	ÖNORM EN 12464-1 and -2 for working spaces (1= indoor, 2 = outdoor spaces) ÖNORM EN 15193
China	GB 50034-2013, GB 50189-2015
Denmark	DS/EN ISO 12464-1 (Tables 5.1–5.53)
Estonia	Requirements for building service systems. Ministry of Economic Affairs and Communications' Ordinance No. 70. RT I, 09.11.2012, 12
Germany	DIN 18599-4, DIN 5035 T 1-14
Latvia	LVS EN 12464-1:2011, LVS EN 12464-2:2014, LVS EN 15193:2009
UK	BS EN 12464-1:2011, Non-Domestic Building Services Compliance Guide: 2013, Non-Domestic Building Services Compliance Guide for Scotland: 2015
USA	ANSI/ASHRAE/IES Standard 90.1, IESNA Recommended Practices, 10th edition, 2010

- Use high-efficacy versions of lamps (e.g., 3100 lumen fluorescent T8).
- Illuminate walls and ceilings to increase perception of brightness.
- Use daylight responsive lighting controls in frequently occupied spaces with daylight access.
- Use occupancy sensors in spaces without daylight access.
- Control lighting with astronomic time-clocks for building-wide energy conservation.

There are numerous international guidelines for lighting systems retrofits (e.g., Robinson 1993, USACE 2013, CEN 2011, ZVEI 2005). The US Army Corps of Engineers (USACE) *Lighting Design Guide* (USACE 2013) that has been adopted by the Annex 61 provides best practice guidance for lighting strategies in different building types and spaces along with illumination levels and maximum lighting power density (LPD) (Table 9).

HVAC SYSTEMS

When building heating, cooling, and electrical loads are significantly reduced, the importance of selecting one type of heating and cooling system over another diminishes. However, a few aspects need to be addressed to achieve DER:

Table 9. Illuminance and LPD Targets for Some Building Spaces (USACE 2013)

Space Type	Target Luminance		Target LPD	
	fc	lux	W/ft^2	W/m^2
Common Spaces				
Conference room	40	430	0.80	8.90
Corridor	10	108	0.50	5.56
Living quarters	5–30	54–323	0.60	6.67
Mechanical/electrical	30	323	0.70	7.78
Reception/waiting	15–30	161–323	0.50	5.56
Restroom/shower	20	215	0.80	8.90
Stair	10	108	0.50	5.56
Storage (general)	10	108	0.50	5.56
Telecom/SIPRnet	50	538	1.20	13.33
Vault	40	430	0.70	7.78
Restaurants/Cafeteria				
Dining Area	20	215	0.60	6.67
Dishwashing/tray return	50	538	0.65	7.22
Kitchen/food prep/drive through	50	538	0.65	7.22
Storage (dry food)	10	108	0.70	7.78
Training				
Readiness bay	40	430	0.75	8.33
Educational/training room (small)	15–30	161–323	0.70 W	7.78
Education				
Kindergarten classroom	15–30	161–323	0.70	7.78
High school classroom	15–30	161–323	0.70	7.78
Active play room	30–50	323	0.50	5.56
Staff lounge	15–30	161–323	0.50	5.56
Warehouse				
Warehouse/receiving/issue bay	40–60	430	0.80	8.90
Vehicle Maintenance				
Consolidated bench repair	50	538	0.60	6.67
Repair bay/vehicle corridor	50	538	0.85	8.89
Hangar				
Maintenance bays	50–70	538	1.0	11.11
Allied shop	50–60	538	1.0	11.11
Production control	25–30	269–323	0.60	6.67
Athletic gym	40–50	430–538	0.70	7.78
Gym with jogging track	50–60	538	0.80	8.90
Racquetball	50	538	1.10	12.22
Combative	50	538	0.90	10.00
Health				
Resident work area	30–45	323	0.40	4.44
Nurses station	15–30	161–323	0.80	8.90
Exam room	30–50	323–538	0.60	6.67

- When replacing HVAC systems with new ones, use high-performance motors, fans, furnaces, chillers, boilers, etc. according to the current national standard and requirements for energy systems.
- Separate systems for ventilation, makeup air, humidity control, and building pressurization from systems providing temperature control. Use dedicated outdoor air systems (DOASs).
- Use well sealed and insulated ducts and insulated hot-water and chilled-water pipes.
- Use energy recovery from return air to preheat and pre-cool outdoor supplied by DOAS.

DOAS. A DOAS delivers 100% outside air (OA) to each individual space in the building via its own duct system (Pagan-Vazquez et al. 2015) for ventilation, makeup air, humidity control, and building pressurization. Heating and cooling of building spaces is provided by a separately controlled system (Figure 1). DOAS airflow rates generally are dictated by the following:

- Indoor air quality needs (based on national standards)
- Latent load (humidity control needs)
- Makeup air for bathroom and kitchen exhausts (when needed)
- Building pressurization to prevent infiltration, which helps to reduce heating/cooling and moisture loads

As a general rule, a DOAS operates at constant volume. For most applications, the DOAS cannot meet all of the thermal loads in the space by itself; it requires a parallel system to accommodate any sensible and latent loads the DOAS cannot accommodate.

The thermodynamic state of the delivered air varies, but at a minimum, it should condition the air to the desired space dew-point temperature (DPT), thus decoupling much of the latent load from the parallel system charged with the bulk of the space sensible load control.

Important cost reducing factors to consider when estimating the economics include (ASHRAE 2008a; ASHRAE 2012; Mumma 2010):

- Chiller size reduction (often 40% or more) due to need for less OA and heat recovery in the DOAS

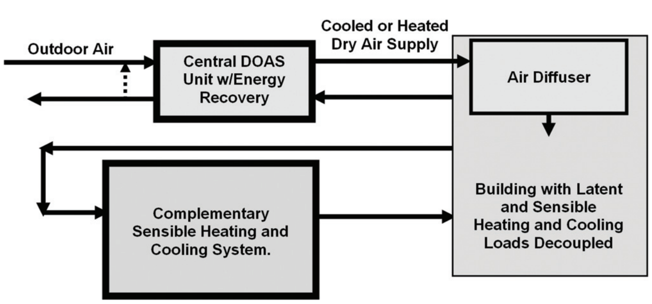


Figure 1 *DOAS schematic.*

- Pump size reduction due to chiller size reduction
- Ductwork reduction due to the small (only about 15% to 20%) DOAS airflow rate when compared to an all air variable-air-volume (VAV) system
- Plenum depth reduction and the associated savings in building enclosure/interior partition/structural/plumbing/fire protection/vertical transportation materials due to the smaller ducts
- Air-handling unit size reduction—depending on the parallel system type
- Electrical services reduction for the mechanical equipment due to smaller chiller, fans, and pumps
- Mechanical shaft reduction due to the much lower air volumes.

An equally important consideration is the impact of improved indoor air quality and avoidance of extremely costly mold remediation projects resulting from high indoor air humidity.

In buildings that are often under partial occupancy, possible energy waste due to excessive outdoor air intake in conventional HVAC systems can be avoided. In DOAS, the amount of conditioned air for thermal load conditioning can be adjusted locally without compromising indoor air quality. An HVAC system can improve its overall energy savings of 15% to 30% by using a DOAS (Mumma 2010).

Heat Recovery

Heat recovery is an important component of the DOAS that allows cooling and heating energy transfer from return air to the outdoor supply air. Energy transfer effectiveness is defined as an actual energy transfer between return and supply air streams. The maximum possible energy transfer between these streams can vary between 60% and 85% with a typical value for cross-flow arrangement about 75% (Harvey 2006). Heat recovery efficiency using the synthetic counter-flow heat exchanger (Brink n.d.) can be up to 95%. Table 10 lists minimum standards for heat recovery equipment, which has been adopted in Annex 61, *Deep Energy Retrofit Guide* (IEA 2016)

For ventilated only (not air-conditioned) buildings, energy recovery is generally more cost effective in cold and moderate climates with a payback ~2 years. For air-conditioned buildings, this technology is applicable to all climates. Plate heat exchangers are simple static devices that reduce the risk of cross contamination between air streams. However, they are bulky, and their supply and exhaust ducts must be adjacent (ASHRAE 2011).

Duct Air Leakage

Duct systems account for a large fraction of the energy use in a building. Energy losses occur due to additional fan energy use, convective losses, and ventilation losses. To meet required airflow rates at air terminal devices, the fan must be sized to specifications and operated under conditions that are detrimental to energy use. To ensure that each room in a building is properly ventilated, the total airflow rate through the

Table 10. Minimum National Standards and Requirements for Heat Recovery from Return Air

Country	Standard for HR Equipment	Energy Type Recovered (Total, Sensible, Latent)	Efficiency, %
Austria	ÖNORM EN 13141-7	Total	70
China	GB 50189-2015	Total and sensible	60
Denmark	Danish Building Regulations BR10 (Building Regulations 2010)	Sensible	70
Estonia	Ordinance No. 70. RT I, 09.11.2012, 12	Sensible	70
Germany	DIN 4108-6, DIN 4701-10, DIN EN 13053, EnEV 2014	Total	50 in average (depending on m^3h (cfm) and h/a the range is 0.4–0.65 [40–65])
Latvia	Latvian Construction Standard LBN 231-15 of 16 June 2015	Not defined	Not defined
UK	Non-Domestic Building Services Compliance Guide: 2013 Non-Domestic Building Services Compliance Guide for Scotland: 2015	Sensible	Plate: 50 Heat pipe: 60 Heat wheel: 65 Runaround coil: 45
US	ANSI/ASHRAE/IES Standard 90.1-2010	Total	>50

central air-handling unit should be high enough to compensate for any leakages in the ducts between the unit and the rooms. This in turn affects the electrical power consumed by the fans.

Duct airtightness classes A to D (Table 11) are defined in European Standard EN 12237 (for circular ducts) and EN 1507 (for rectangular ducts). Class A is the leakiest class. A new standard for airtightness of ductwork components EN 15727 was published in 2010. EN 12599 describes the leakage test method for system commissioning.

Apart from Scandinavia, many countries in Europe have generally very leaky ventilation systems. Leakage rates can be typically three times leakier than Class A, which is up to 30 times higher than is observed in Scandinavia (Guyot and Carrie 2010). Nearly all Swedish buildings and their installations meet the voluntary AMA (Swedish abbreviation for "General Requirements for Material and Workmanship") specification guidelines. AMA is referenced in building contracts between the owner and contractors. One section of the guidelines concerns HVAC (VVS AMA). The current (1998) version of VVS AMA requirements for duct system airtightness includes the following:

- Class A (the lowest level allowed) applies to visibly installed ducts in the space being served. A leakage here will not have any real significance, as the leakage airflow is beneficial to the space.
- Class B (three times tighter than A) applies to all rectangular duct systems and any duct systems with surface area ≤20 m^2 (215 ft^2). Surface area is determined according to EN 14239. This generally applies to small houses.

Table 11. Duct Airtightness Classes per EN 12599 (BSI 2012)

Airtightness Class	Limiting Leakage, $(L/s)/m^2$ (cfm/ft^2)
A – worst	<1.32 (0.26)
B	<0.44 (0.09)
C	<0.15 (0.03)
D	<0.05 (0.01)

- Class C (three times tighter than B) applies to round duct systems with surface areas >20 m^2 (215 ft^2). This applies to the vast majority of buildings. Class C round ductwork has typically 30% less fan power than traditional Class A ductwork.
- Class D (three times tighter than C) is not a standard requirement but can optionally be specified for systems in which airtightness is essential. This normally calls for round duct systems with double gaskets (see figures above).

The three ingredients for success are as follow:

- Increased awareness of the benefits of quality round ductwork
- Establishing guidelines and requirements, ideally with incentives (which should be included in building contracts)
- Verification of guidelines and requirements in each project, with predefined penalties

Airtight systems facilitate exploitation of the full benefit of other energy efficiency measures, including demand-control and heat recovery. This affects the energy use for both heating and cooling. French calculations ((Guyot and Carrie 2010) show that air leaking out of the ducts can reduce the global efficiency of a heat recovery system from 85% (nominal value) to less than 60% (ducts three times leakier than Class A ducts). This equates to approximately 5 kWh/m^2/yr (1.58 kBtu/ft^2/yr) of space heating.

Duct Insulation

Duct insulation saves energy and keeps warmed or cooled air as close to a desired temperature as possible while it is being moved to spaces where it is needed. If reduced heat transfer through insulated ducts is accounted for in the HVAC load calculations, it may even be possible to reduce the size of HVAC equipment. Requirements for duct insulation are stated in national codes (listed in Table 12); levels of insulation depend on the building climate zone and duct location (attic, crawlspace, basement, inside conditioned space, or other). Return ducts connected to heat recovery equipment should also be insulated. Duct insulation is installed for energy conservation and also to reduce noise and to control condensation. Insulation must be protected from damage, including that due to sunlight, moisture, and equipment maintenance.

Insulation of Hot- and Cold-Water Pipes

Piping that serves as part of a heating, domestic hot water, or cooling systems should be terminally insulated to reduce energy loss and eliminate moisture condensation on cold piping surfaces. This also applies to chilled water, liquid refrigerant, cooling coil condensate, storm water roof drainage, and domestic cold-water piping systems with a temperature below 60°F (15.6°C) or below the adjacent space DPT. All piping, fittings, and devices should be insulated and be provided with a well sealed vapor barrier applied to the entire insulation system to prevent diffusion of water vapor into the insulation system. Exceptions can be made for piping that conveys fluids that have a design temperature range between 60°F (15°C) and 105°F (41°C). The minimum insulation thickness depends on the pipe size and fluid temperature (Table 13).

Modeling Results

The summary of the modeling results conducted under the Annex 61 (Case et al. 2016; Rose et al. 2016; Riel et al. 2016; Yao et al. 2016) (Table 14) shows that, by using only the previously described core technology bundles in major renovation projects, it is possible to reduce building site energy by about 50% compared to the pre-renovation baseline.

Energy reduction (~40%) in hot and warm climates (CZ 1 through 3) will be less dramatic due to the need for humidity control and significant cooling via plug loads. In cold and moderate climates, achieving 50% or better site energy use reduction does not present a problem. DER using only core technology bundles also results in significant source energy use reduction (35% and better). Modeling results have demonstrated that further site energy use reduction (up to 80% in moderate climates, i.e., achievement of the "national dream") is technically possible with the use of some additional energy efficiency technologies and plug load control. Source energy is significantly reduced (60%–70%) as well. Use of building dedicated renewable energy sources (e.g., PV and solar water heating) or heat pumps will further reduce both building site and source energy.

Table 12. Duct Insulation Requirements

Country	Standard for Duct Insulation	Insulation Requirements
Austria	ÖNORM H 5057	U-factor 0.6 W/(m^2·K) (0.106 Btu/[h·ft^2·°F])
China	GB50736-2012	U-factor 1.234 W/(m^2·K) (0.217Btu/[h·ft^2·°F]) —Normal air conditioning duct) 0.877 W/(m^2·K) (0.154 Btu/[h·ft^2·°F]) —Low temperature air conditioning duct)
Denmark	Danish Standard 452	0.36–1.40 W/(m^2·K) (0.063–0.246 Btu/[h·ft^2·°F])
Estonia	EVS-EN 13779: 2007, EN 12097	0.36–1.4 W/(m^2·K) (0.063–0.246 Btu/[h·ft^2·°F])
Germany	EnEV 2014	20–200 mm (0.79–7.87 inch) dependent on pipe diameter and surrounding air temperature
Latvia	LVS EN 13779: 2007	0.36–1.4 W/(m^2·K) (0.063–0.246 Btu/[h·ft^2·°F])
UK	BS 5422: 2009	5–12 0mm (0.2–4.7 in)* (condensation control) 6.45 W/m^2 (2 Btu/ft^2·h) (chilled or dual-purpose duct heat gain control) 16.34 W/m^2 (5.2 Btu/ft^2·h) (duct works carry warm air heat loss control)
USA	ANSI/ASHRAE/IES Standard 90.1-2013 (Table 6.8.2B)	U-factor 0.7–1.62 W/(m^2·K) (0.125–0.2860 Btu/[h·ft^2·°F]) —supply and return for heating or cooling U-factor 0.95–1.62 W/(m^2·K) (0.167–0.286 Btu/[h·ft^2·°F])—return ducts

*Depending on pipe radius and temperature difference.

Table 13. Hot-Water and Cold-Water Pipe Insulation Requirements

Country	Minimum Standard	U-Factor or Other Requirement
Austria	OIB RL 6, 2011	Insulation = pipe diameter with thermal conductivity of the insulation material of 0.035 W/(m·K) (0.24 Btu·in./[h·ft^2·°F]) Cold/chilled water: 0.6–0.7 W/(m^2·K) (0.106–0.124 Btu/[h·ft^2·°F]), hot water: 0.7 W/(m^2·K) (0.124 Btu/[h·ft^2·°F])
China	GB50736-2012	Hot water pipe: 25–140 mm (1.0–5.5 in.) Chilled water pipe: 19–60 mm (0.7–2.4 in.) Condensation water pipe: 9–15 mm (0.4–0.6 in.)
Denmark	Danish Standard 452	Cold/chilled water: 0.33 W/(m^2·K) (2.28 Btu·in./[h·ft^2·°F]); hot water: 0.11–0.24 W/(m^2·K)* (0.76–1.66 Btu·in./[h·ft^2·°F])
Estonia	*Buildings General Quality Requirements* (*Hoone Tehnosüsteemide*) RYL 2002, Chapter "G9 Insolation" LVI 50-10344, *Talotekniikassa yleisesti käytettävät eristysmateriaalit ja niiden asennus* (in Finnish) LVI 50-10345, *Taloteknisten eristysten mitoitus ja käyttö* (in Finnish)	Cold/chilled water: ≈1.5 W/(m^2·K) (10.4 Btu·in./[h·ft^2·°F]); hot water: ≈0.5–0.8 W/(m^2·K)* (3.47–5.55 Btu·in./[h·ft^2·°F])
Germany	EnEV 2014	Hot-, cold-, and chilled-water pipe: 20–200 mm (0.79–7.87 in.) dependent on pipe diameter and surrounding air temperature
Latvia	Construction Standard LBN 221-15 of 30 June 2015	Requirement for pipe insulation defined, while U-factors are not provided
UK	BS5422: 2009	Insulation requirement Cooled and chilled-water systems, cooled-water temperature >10°C (50°F), 2.48–14.74 W/m (2.58–15.33 Btu/[h·ft]) Cooled and chilled-water systems, chilled-water temperatures >4.9 °C to <10 °C (40.8°F to 50°F), 2.97–16.28 W/m (3.09–16.93 Btu/[h·ft]) Cooled and chilled-water systems, chilled-water temperatures of 0 °C to <4.9 °C, (32°F to 40.8°F) 3.47–17.48 W/m (3.61–18.18 Btu/[h·ft]) Nondomestic hot-water service: 6.6–32.4 W/m (6.86–33.70 Btu/[h·ft]) Domestic heating and hot-water systems: 7.06–14.12 W/m (7.34–14.68 Btu/[h·ft]) Nondomestic heating services, low-temperature heating services, ≤95°C (203°F), 9.26–38.83 W/m (6.86–40.38 Btu/[h·ft]) Nondomestic heating services, medium-temperature heating systems, 96°C–120°C (205°F–248°F), 13.34–43.72 W/m (6.86–40.38 Btu/[h·ft]) Nondomestic heating services, high-temperature heating systems, 121°C–150°C (250°F–302°F), 17.92–48.48 W/m (18.64–50.42 Btu/[h·ft])
US	ANSI/ASHRAE/IES Standard 90.1-2013 (Tables 6.8.3 A and B)	Heating and hot water pipes* 40°C–60°C (105°F–140°F); 1.25–2.38 W/(m^2·K) (0.22–0.42 Btu/[h·ft^2·°F]) 61 °C–93 °C(141°F–200°F); 2.12–3.28 W/(m^2·K) (0.375–0.58 Btu/[h·ft^2·°F]) Cooling Systems pipes*: 4°C–16°C (40°F–60°F); 0.6–1.53 W/(m^2·K) (0.105–0.27 Btu/[h·ft^2·°F]) < 4°C (< 40°F); 0.57–2.2 W/(m^2·K) (0.1–0.39 Btu/[h·ft^2·°F])

*Depending on pipe inner diameter

QUALITY ASSURANCE

High levels of energy use reduction using core technology bundles along with improvements in indoor climate and thermal comfort can be only achieved when a DER adopts a product delivery quality assurance process that includes the following:

- Formulation of detailed technical specification (e.g., statement of work [SOW] or owner's project requirements document [OPR], against which tenders [i.e., bids] will be made) and verification that potential contractors understand these specifications
- Specification in SOW/OPR of areas of major concern to be addressed and checked during the bid, including the selection, design, construction, commissioning, and post-occupancy phases

Table 14. Potential for Site and Source Energy Use Reduction (Compared to the Baseline) for DER Projects Using Core Bundles of Technologies and Beyond

Climate Zone	Baseline			Base Case		DER			HPB	
	Total-site EUI (100%), kWh/m²·yr (kBtu/ft²·yr)	Site EUI for Heating (100%), kWh/m²·yr (kBtu/ft²·yr)	Source EUIt (100%), kWh/m²·yr (kBtu/ft²·yr)	Site Energy Use Reduction, %	Source Energy Use Reduction, %	Site Energy Use Reduction, %	Site Heating Energy Use Reduction, %	Source Energy Use Reduction, %	Site Energy Use Reduction, %	Source Energy Use Reduction, %
Public Housing, Austria										
5A	218 (69)	152 (48)	210 (67)	38	31	50	73	64	55	68
7	253 (80)	184 (58)	235 (75)	47	36	50	68	62	55	68
Office Building, China										
2A	3 (1)	105 (33)	331 (105)	37	37	47	56	47	54	54
3A	25 (8)	119 (38)	378 (120)	38	38	51	62	51	65	65
3C	8 (3)	77 (24)	243 (77)	36	36	47	64	47	69	69
4A	117 (37)	201 (64)	393 (125)	42	42	53	71	41	62	55
7	239 (76)	306 (97)	472 (150)	32	33	50	62	38	67	59
School Building, Denmark										
6A	252 (80)	210 (67)	314 (99)	19	16	56	67	45	82	63
Dormitory, Estonia										
6A	153 (49)	213 (68)	225 (71)	29	22	47	69	37	70	58
Office Building, Germany										
5A	256 (81)	220 (70)	307 (97)	40	27	55	58	53	81	76
Office Building, UK										
4A	89 (28)	155 (49)	291 (92)	20	16	51	84	32	58	42
5A	135 (43)	201 (64)	341 (108)	23	20	60	83	42	67	52
Barracks, US										
1A	1 (0)	398 (126)	1154 (366)	17	19	39	59	42	59	59
2A	33 (10)	380 (121)	1025 (325)	17	18	41	84	42	60	59
2B	17(5)	365 (116)	1008 (320)	17	18	40	80	42	61	61
3A	65 (21)	394 (125)	965 (306)	19	18	45	84	42	63	59
3B	37 (12)	326 (103)	812 (258)	15	14	39	82	37	60	57
3C	35 (11)	273 (87)	634 (201)	12	9	33	70	31	46	37

Table 14. Potential for Site and Source Energy Use Reduction (Compared to the Baseline) for DER Projects Using Core Bundles of Technologies and Beyond *(Continued)*

Climate Zone	Baseline			Base Case		DER			HPB	
	Total-site EUI (100%), kWh/m²·yr (kBtu/ft²·yr)	Site EUI for Heating (100%), kWh/m²·yr (kBtu/ft²·yr)	Source EUIt (100%), kWh/m²·yr (kBtu/ft²·yr)	Site Energy Use Reduction, %	Source Energy Use Reduction, %	Site Energy Use Reduction, %	Site Heating Energy Use Reduction, %	Source Energy Use Reduction, %	Site Energy Use Reduction, %	Source Energy Use Reduction, %
4A	103 (33)	397 (126)	869 (276)	20	16	48	85	25	65	59
4B	86 (27)	333 (106)	745 (236)	16	12	42	88	35	62	56
4C	111 (35)	330 (105)	678 (215)	18	12	44	86	35	62	55
5A	160 (51)	422 (134)	872 (277)	21	17	51	87	42	67	60
5B	133 (42)	362 (115)	733 (233)	18	13	52	88	37	65	57
6A	212 (67)	448 (142)	839 (266)	22	16	55	88	44	70	61
6B	192 (61)	414 (131)	773 (245)	21	14	53	89	41	69	60
7	283 (90)	508 (161)	878 (279)	24	18	59	88	47	73	63
8	417 (132)	630 (200)	978 (310)	24	18	64	92	52	77	67
Office Building, US										
1A	24 (7)	261 (83)	815 (259)	30	27	48	91	45	66	64
2A	60 (19)	285 (90)	814 (258)	32	28	46	63	43	70	65
2B	81 (26)	314 (100)	862 (273)	36	29	49	87	41	73	91
3A	82 (26)	288 (91)	771 (245)	34	28	47	63	43	71	64
3B	68 (22)	251 (80)	680 (216)	30	23	51	92	41	66	58
3C	45 (14)	183 (58)	507 (161)	26	16	41	96	30	59	51
4A	96 (30)	271 (86)	685 (217)	35	26	50	89	38	69	60
4B	71 (22)	227 (72)	593 (188)	31	21	50	95	37	63	54
4C	76 (24)	206 (65)	513 (163)	31	18	48	96	33	63	52
5A	107 (34)	270 (86)	656 (208)	35	25	50	87	37	69	58
5B	83 (26)	223 (71)	552 (175)	31	20	50	95	35	64	53
6A	121 (39)	265 (84)	606 (192)	36	23	52	88	36	69	55
6B	118 (38)	254 (81)	575 (182)	34	22	51	88	34	68	55
7	145 (46)	278 (88)	594 (189)	39	24	54	87	36	71	55
8	218 (69)	340 (108)	634 (201)	42	27	59	83	39	76	58

- Clear delineation of the responsibilities and qualifications of stakeholders in this process

This process can be applied to major renovation projects using both design-bid-build and design-build procurement methods. Some elements of this process can be used also with minor renovation and system replacement projects.

The product delivery quality assurance process (PDQA) can be divided into five phases:

1. Development of the SOW or OPR that provides clear and concise documentation of the owner's goals, expectations, and requirements for the renovated building that should be used throughout the project delivery and that provide an informed baseline and focus for design development and for validating the building's energy and environmental performance. Based on this document, bidders will be able to offer a matching perspective.
2. Procurement phase, which includes an analysis of bidders' qualifications, of their understanding of the SOW and its requirements, and of their previous experience and ability to coordinate different trades and to deliver a renovated building that will meet specifications.
3. Design phase with design reviews and design.
4. Construction and whole building commissioning.
5. Post occupancy evaluation.

SOW Development. It is important that the SOW and bids include specific energy targets (i.e., EUI for site and primary energy, kBtu/ft^2 or kWh/m^2 per year, energy security and system redundancy requirements) to be achieved through the building renovation. The SOW and bids should also include the parameters and qualities of materials, components and building systems to be used, installation methods, and testing and commissioning methods that will be used for verification throughout the design, construction, and post-occupancy phases. Adding specificity in the SOW/OPR and bids will ensure that these requirements become contractually binding.

During the bidding and design phases, the contractor provides results of energy modeling to demonstrate theoretical feasibility of meeting energy targets.

For the bidders to prepare an accurate energy model and retrofit proposal, the SOW/OPR should include the following information:

1. Building utility consumption data for one to two years
2. Building operating schedule before renovation
3. Number of occupants, occupant schedule, and activity level
4. Design drawings for the building envelope showing existing wall, floor, and roof construction
5. Design drawings showing building/floor layout
6. Building orientation
7. Existing window characteristics (type, size, number, average U-factor of the window with a frame and a U-factor at the center of the glass, type of glazing, SHGC)
8. Types of HVAC system and equipment list (for both cooling and heating systems)
9. List of existing lighting fixtures (types and quantities)
10. Plug loads (types, quantity, and power consumption requirements)
11. Submetering data, if available

The pre-renovation building model should be calibrated against the utility data.

If the use and building schedules remain unchanged through the renovation, the input data listed in elements 2, 3, and 11 above are used for modeling of the post-renovation scenario. If the use and schedules of the building will change, this information should be provided in the SOW/OPR and used for the post-renovation building model.

Bidding Phase. For the bidding process, it is important that the contractor present a review of the energy requirements for the project to include site and source energy targets, energy calculation, and modeling methodologies. It is also important for the contractor to discuss and resolve any conflicts or questions regarding the SOW/OPR. The models presented during the bidding and design processes should provide an initial list of all energy parameters for the project to include operational runtimes, load peaks/schedules, equipment efficiencies/setpoints/sizes, insulation values, etc. Each entry/value should be identified as being supplied from the project SOW, a specific design guide, and a specific energy standard. These models must be calibrated against the baseline energy values of the building before DER and must show building schedules before and after renovation. The modeling results should verify that the proposed design meets the owner's energy targets, and the owner should review the results to ensure assumptions and calculations are valid.

The bid and design should not be accepted if the energy targets are not met. If the contractor cannot meet the energy targets within the bounds of the SOW, a review of the problems or constraints should be presented along with a list of necessary changes or upgrades.

Potential bidders should be requested to submit information reflecting past experience with energy-focused building renovation projects. They should include narratives and examples of technical solutions that are relevant to renovation projects involving similar building types: (e.g., they should show how air barriers were installed, tested, and verified; show examples of proper detailing of continuous insulation; provide examples of energy efficient HVAC and lighting systems).

Bidders will be evaluated based on past performance and on their technical capacity and understanding of the USACE air barrier quality control process (referenced in the request for proposal [RFP]). Examples should show their proficiency in executing work as required by the RFP. Bidders will be also evaluated on their past performance, specifically on their proficiency in designing similar types of building renovation and in designing a renovation inside a constrained building shell.

During the pre-bidding process, prospective bidders should be offered a site visit with a building walk through to get an idea of the existing building conditions and space available for mechanical equipment, to validate information for the energy model, and to clarify issues that can arise during the SOW/OPR review.

Design and Construction Phases. During the design and construction phases, special attention must be paid to architectural details to be used for the building envelope renovation; continuity of thermal, water, vapor, and air barriers; windows and their installation techniques; control systems; etc.

It is important that the measurement and verification (M&V) process be specified and that it include measurement of all types of energies supplied to the building during the first year (or two years, if necessary), pressure test of the building envelope and ducts using established protocols, and a thermographic evaluation of the building envelope showing the areas of the building envelope leakage and thermal bridges.

Once established, a product delivery quality assurance process will have a significant effect on the building performance improvement. Based on lessons learned, it can be later streamlined and implemented at a minimal or no additional cost.

ECONOMIC ANALYSIS

Buildings usually undergo major renovations for many reasons, including the need to reduce energy consumption. Some of the most common reasons include the following:

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

Timing a DER to coincide with a major renovation is best since the building is typically evacuated and gutted; scaffolding is installed; single pane and damaged windows are scheduled for replacement; building envelope insulation is replaced and/or upgraded; and most of mechanical, electrical lighting, and energy conversion systems (e.g., boiler and chillers) along with connecting ducts, pipes, and wires will be replaced. A significant sum of money covering the cost of energy-related scope of the renovation designed to meet minimum energy code is already budgeted. Therefore, it is reasonable to conduct an LCC analysis with the incremental first and replacement cost increase (ΔC) required achieving DER compared to original project budget. This delta cost increase is based on difference in energy (ΔE) used by the projected building after the DER minus the building renovated to the current minimum standard. Because most of parameters required for LCC analysis differ not only by the individual country but also within the country (first costs and labor rates, energy rates, life of the project, inflation and discount rates, etc.), the following methodology has been proposed for evaluation of LCC analysis effectiveness of the integrated energy technology bundle to be used for DER:

Step 1. Calculate annual energy use and cost per scenario (the most stringent between >50% of the baseline or minimum requirement of the national standard for building renovation).

Step 2. Calculate annual energy use and cost per scenario (use the baseline, Step 1, if there is no national minimum energy requirement for renovated buildings).

Step 3. Subtract energy cost calculated in Step 2 from the one calculated in Step 1 and calculate net present value (NPV) of energy savings over the project life using scalar ratio, described in the next section.

Step 4. NPV of energy savings can be used to estimate the budget increase limit compared to the base case for all scenarios, which can be used for energy enhancements with DER compared to building renovation based on minimum energy requirements.

The budget increase allowance will depend on the difference in operational costs savings resulting from reduced energy cost, reduced maintenance and system insurance costs, and, when applicable, from increased revenues from rent of space. In buildings after DER, reduced thermal loads reduce HVAC system's size and complexity resulting in reduced O&M costs. Per RMI (Bendewald et al. 2014), high-performance buildings have 9%–14% smaller maintenance costs compared to the business-as-usual baseline. German Standard VDI 2067 (VDI 2012) and Danish Green Building Council (DK-DGNB 2014) provide estimates for maintenance costs as a percentage of the building system cost.

A DER that results in a lower energy and sustainable building will accelerate lease-up time versus average market downtime and provide additional value (i.e., the property can be leased for a rent 9%–14% higher than that of comparable unimproved properties in the local market). Also, many DER projects result in adding rentable/usable space (e.g., due reduced size of mechanical rooms, adding thermally controlled areas [mansards, basements, repurposing storage spaces, etc.]), which can be accounted for in the estimation of the budget increase allowance.

The budget increase allowance (ΔBudget) can be calculated using fundamental formula for NPV calculation can be presented as following:

$$\Delta Budget_{max} = NPV\ [\Delta Energy\ (\$)] + NPV\ [\Delta Maintenance\ (\$)] + NPV\ [\Delta Replacement\ Cost\ (\$)] + NPV\ [\Delta Lease\ Revenues\ (\$)]$$

where NPV [ΔEnergy ($)] is a present value of future energy cost savings for the project with the project life of N years, due to reduced use of electricity (E), gas (G) and other fuels (OF).

$$\text{NPV}[\Delta\text{Energy}(\$)] = \text{NPV}[\Delta E \times C_E] + \text{NPV}[\Delta G \times C_G] + \text{NPV}[\Delta OF \times C_{OF}]$$

where

CE, CG, COF = unit fuel prices

ΔE, ΔG, ΔOF = annual electricity, gas, and other fuel saving

For each fuel type, NPV of energy cost saving NPV can be calculated using the following formula (examples is provided for gas):

$$\text{NPV}[\Delta G \times C_G] = [\Delta G]_{t=1} \times C_{G(t=1)} \times \sum_{t=N}^{t=1} \text{It} \times [(1+d)^N - 1]/[d(1+d)^N]$$

where It is the projected average fuel price index. For the United States, projected average fuel price index is tabulated in (VDI 2012):

$C_{G(t=1)}$ – gas unit price in the first year

To simplify calculations, the energy unit price change from year to year can be assumed to be at a constant rate (or escalation rate) over the study period. The escalation rate (Table 15) can be positive or negative. The formula for finding the present value (NPV [$\Delta G \times C_G$]) of an annually recurring cost savings at base-date prices ($C_{G(t=1)}$) changing at escalation rate e is as follows:

Table 15. Ranges of Escalation and Discount Rates for Annex 61 Participating Countries (2015 Data)

Country	Discount Rate	Escalation Rate
Austria	2.2%	3.9%—electricity 4.8%—district heating
China	2.25%	2%
Denmark	2%	4%
Estonia	4.0%	3.0%
Germany	2.5%	0%, 2%, and 4%
Latvia	3.5%	0.9%
UK	3.5%	1.5%
US (Lavappa and Kneifel 2015)	DOE –3% OMB short term (< 7 yrs) projects): 0.7%, OMB long term (>30 yrs projects):1.4%	2.8—electricity 3.8—gas Nominal annual escalation rate averaged across all states at disc rate of 2.1% (for specific location and discount rate, use EERC 2.0-15 tool)

$$\text{NPV}[\Delta G \times C_G] = [\Delta G]_{t=1} \times C_{G(t=1)} \times (1+e)/d - e) \times [1 - (1+e)/1+d)]^N$$

NPV [ΔMaintenance ($)] = present value of future maintenance cost savings

NPV [ΔReplacement Cost ($)] = present value of future replacement cost reduction

NPV [ΔLease Revenues ($)] = increase in revenues from the space lease

The formulas for calculating NPV [ΔMaintenance ($)] and NPV [ΔLease Revenues ($)] are based on the discount or inflation rate, d:

$$\text{NPV}[\Delta\text{Maintenance}(\$)] = [\Delta\text{Maintenance}]_{t=1} \times [(1+d)^N - 1]/[d(1+d)^N]$$

where

$[\Delta\text{Maintenance}]_{t=1}$ = maintenance costs savings in the first year

NPV [ΔLease Revenues ($)] = $[\Delta\text{Lease Revenues}(\$)]_{t=1} \times [(1+d)^N - 1]/[d(1+d)^N]$

$[\Delta\text{Lease Revenues}(\$)]_{t=1}$ = lease revenues increase in the first year

$\text{NPV}[\Delta\text{Replacement Cost}(\$)]_T$ = $[\Delta\text{Replacement Cost}(\$)]_T \times (1+d)^T$

$[\Delta\text{Replacement Cost}(\$)]_T$ = equipment replacement cost saving in the year (T).

Please note that the current paper does not address the possibility of financing either any part of the major renovation cost or the cost increase to achieve DER. Therefore, there is no financing cost involved and there is no need to account for the interest rate of financing.

Each term in the formula can be calculated in terms of net present dollars (€) or constant dollars (€). Instead of calculating the NPV of each term, this can be simplified by using economic scalar ratios (SRs) for energy and scalars (S) for maintenance, lease, and replacement. This simplification avoids the difficulty of selecting all of the individual economic parameters in determining the cost effectiveness of projects, thus establishing a comparative economic feasibility threshold for analysis.

The SR is a summation of the annual present worth factors over project study life to produce a single present value factor (see McBride 1995 for detailed development). In estimation of NPV of energy savings, the discount factor is ratioed with the fuel cost scalars to form the SR used in the economic analysis. The equation below shows the usage of the SR and S, simplified by neglecting the replacement value:

$$\Delta\text{Budget}_{max} = SR_E[\Delta\text{Energy}(\$)] + S_M[\Delta\text{Maintenance}] + S_L[\Delta\text{Lease Revenues}]$$

S_M and S_L scalars can be calculated and are the uniform present worth factor series that use the discount rate, the same way as SR_E with the escalation rate $e = 0\%$.

Figure 2 shows examples of SRs and Ss calculated at for a range of Discount (Dsc) and Escalation (Esc) values. These sample calculation are presented to demonstrate the sensitivity of the scalars with varying input values. The data in Table 16 indicate that with Int = 0%, Dsc = 0%, and Esc = 0%, the SR is equal to the study life. Other calculations in Table 16 demonstrate how the interest rate and the cost of money decrease SR, or cost effectiveness, and fuel escalation increases the SR. Changes in the SR change the budget that can be spent economically on the project. For simplicity, the federal and state taxes are being held constant, but are incorporated in the SR as necessary. Table 15 also lists the scalars that are applied to maintenance, lease, and replacement cost Δ values and that are just the uniform present worth value summation for study life. Individual values can be applied as necessary for each term, depending on the years for the item of interest. If the SR and S are close in value then these can all be simplified to one SR for clarity. Table 16 lists ranges of country-specific values of discount, escalation, and interest rates.

SRs are not uniform present-worth factors, but are used in a similar fashion, in that they are factors that are multiplied by the calculated single year energy savings to arrive at the present value cost. In addition, SRs are not equivalent to simple payback (SPB) since they account for the time value of money. Scalars are uniform present worth factors that are used similarly to SRs.

The usage of the SR in the context of the DER is the main focus in this paper. Economic analysis for projects can be calculated by two methods, either absolute or incremental. The first method calculates the total LCC given all of the project costs; the second method calculates the annual savings and uses the incremental costs associated with that annual savings. The steps described in the previous section and in the example below show an incremental method approach.

Example of Allowable Budget Increase Calculation with DER

This example calculation is for a 8830 m^2 (95,042 ft^2) barracks that is undergoing a DER. The analysis shows the base case and the integrated energy efficiency packages that are added in addition to the standard retrofit. These packages include lighting, infiltration reduction and envelope enhancements, and HVAC improvements. The base case is calculated with the standard retrofit options and the integrated package with the increased efficiency options from the base case. The Δ cost increase from the base case is shown and determined from standard values. Then, for a project life of 25 years, the Δ energy cost savings is calculated with the SPB.

For the renovation using the core technologies bundle accumulated annual Δ, savings will be as follows:

$$\Delta\text{Energy Cost Saving } \$ = \$208{,}427 - \$124{,}845 = \$83{,}582 \text{ savings/yr}$$

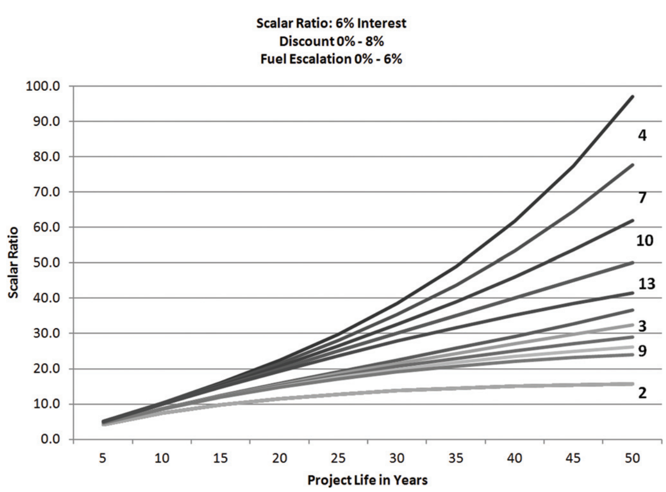
and an SPB available budget is calculated as follows:

$$\text{SPB for 25 yr} = \$83{,}582 \times 25 = \$2{,}089{,}550$$

If there is no cost of money (0% interest) and one uses the same escalation and discount, then the calculated SR = 28.4 where the escalation rate adds to the NPV of money in a LCC calculation and the savings would be as follows:

$$\$83{,}582 \text{ savings/yr} \times 28.4 = \$2{,}373{,}729 \text{ (NPV available budget)}$$

There is a significant difference between the available budget using SPB and that budget if NPV of money is taken into account. The SR does incorporate the economic parameters. With this methodology, it is easier to set a standard or minimum economic hurdle by setting one number versus a series of economic parameters. ASHRAE Standard 90.1 has



(a)

(b)

Figure 2 *(a) Scalar ratio for fuels at varying discount and fuel escalation rates (note: curves are identified with the data listed in Table 16) and (b) scalars for maintenance and leases.*

Table 16. Examples of SRe Calculated for Selected Values of Economic Project Life and Discount and Escalation Rates

No.*	Economic Life (yrs) Discount	Escalation	5	10	15	20	25	30	35	40	45	50
1	0%	0%	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0
2	0%	–1%	4.9	9.5	13.9	18.0	22.0	25.8	29.4	32.8	36.0	39.1
3	0%	1%	5.2	10.6	16.3	22.2	28.5	35.1	42.1	49.4	57.0	65.1
4	0%	3%	5.5	11.8	19.2	27.7	37.6	49.0	62.3	77.7	95.5	116.2
5	2%	–1%	4.9	9.5	13.9	18.1	22.2	26.2	30.0	33.6	37.2	40.7
6	2%	1%	5.1	10.5	16.2	22.1	28.2	34.6	41.2	48.1	55.2	62.5
7	2%	3%	5.5	11.8	18.9	27.1	36.4	46.9	58.7	71.9	86.6	103.0
8	4%	–1%	4.9	9.5	14.0	18.3	22.4	26.5	30.5	34.4	38.3	42.2
9	4%	1%	5.1	10.5	16.1	22.0	28.0	34.1	40.5	46.9	53.5	60.2
10	4%	3%	5.5	11.7	18.7	26.6	35.4	45.0	55.4	66.7	78.9	91.8
11	6%	–1%	4.9	9.5	14.0	18.4	22.6	26.9	31.0	35.2	39.3	43.4
12	6%	1%	5.1	10.5	16.1	21.8	27.7	33.7	39.8	45.9	52.1	58.4
13	6%	3%	5.4	11.6	18.6	26.2	34.4	43.2	52.5	62.3	72.5	83.0
Scalars for Maintenance and Leases Below, Escalation = 0%												
1	0%	0%	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0
2	1%	0%	4.9	9.5	13.9	18.0	22.0	25.8	29.4	32.8	36.1	39.2
3	2%	0%	4.7	9.0	12.8	16.4	19.5	22.4	25.0	27.4	29.5	31.4
4	3%	0%	4.6	8.5	11.9	14.9	17.4	19.6	21.5	23.1	24.5	25.7
5	4%	0%	4.5	8.1	11.1	13.6	15.6	17.3	18.7	19.8	20.7	21.5
6	5%	0%	4.3	7.7	10.4	12.5	14.1	15.4	16.4	17.2	17.8	18.3
7	6%	0%	4.2	7.4	9.7	11.5	12.8	13.8	14.5	15.0	15.5	15.8
8	7%	0%	4.1	7.0	9.1	10.6	11.7	12.4	12.9	13.3	13.6	13.8

*These data (indicated by "No.") relate to the curves in Figure 2a.

adopted the SR to maintain uniform economic stringency throughout the standard. The current value that ASHRAE is using for 2016 development, using a study life of 25 years, is 14.8. ASHRAE also uses: Dsc = 9.34%, Int = 7.0%, federal tax = 0%, state tax = 0%, and fuel escalation = 2.38%.

Table 17 lists results for a 8830 m^2 (95,042 ft^2) barrack analysis starting with the final integrated package with the base case. The "Delta First Cost" column is the cumulative cost of the efficiency options quoted for the integrated package, $1,639,474. When there is no cost of money (basically using an SPB method), there is more than enough budget to cover the improvements. However, using NPV dollars, the financial package needed for this case would be an SR= 20, or a value above that needed to meet the quoted costs for the integrated package to attain 41% savings. With this analysis, you can either work with the financier to bargain for better rates or work with the contractor to establish a quote that fits the available budget. (Note that, for this example, the maintenance costs were neglected for simplicity.) So, for this example, any SR ≥ 20 will be cost effective, so the SR currently used by ASHRAE of 14.8 will not meet the threshold. However, with no need to borrow money or with an interest rate = 0% then the current SR of 28.4 is more than adequate and the initial package could be extended further with the additional available finances.

The SR not only allows for a quick calculation once the analysis is complete, but it makes it easier to calculate and monitor the economic calculation as well. It also allows for

Table 17. Economic Analysis for a Barracks Renovation Project with a 25-Year Project Study Life

	Energy Reduction, %	Electric, kWh (kBtu)	Gas, kWh (kBtu)	Total, kWh (kBtu)	Total Utility Cost, $	Delta First Cost, $	TotalSPB Budget 25 yrs, $	SR = 15	SR = 18	SR = 20	SR = 28.4
Base case (minimum standard)		1,431073 (4,883,022)	2,532018 (8,639,604)	3,963,091 (13,522,626)	208,427						
Energy efficient renovation	41%	878,209 (2,996,573)	1,456,489 (4,969,746)	2,334,698 (7,966,319)	124,845	1,639,474	2,089,550	$1,253,730	$1,504,476	$1,671,640	$2,373,729

quick comparison of one region or country to one another (i.e., a US value compared to a European value). If the United States had an SR = 16 and the European Union (EU) had a value of SR = 22 for a 25-year study life, it would be easy to compare the economic stringency for each compared to all of the individual economic parameters and their effects.

CONCLUSION

The core technology bundles described in this paper make it possible to achieve DER with major renovation of buildings with low internal loads (e.g., office buildings, dormitories, barracks, and educational buildings). This task is more difficult in hot climate zones (DOE CZ 1 through 3) with significant cooling needs and may require additional energy efficiency measures to be applied (e.g., reduction of plug loads, water conservation measures, advanced HVAC systems). DER is easier to achieve in heating dominated climates and in cases when either by cultural or normative reasons, cooling is not desired and building users can tolerate temporary increases in indoor air temperature (e.g., up to 77°F [25 °C]).

In building simulations conducted for locations in China, the pre-renovation baseline (based on pre-1980s design) was developed for a naturally ventilated office building with inferior insulation levels and poorer building airtightness, as compared to European countries and the United States. This resulted in lower insulation levels of the building envelope and window characteristics required for the deep energy retrofit scenario (50% energy use reduction compared to the baseline) presented in Tables 4 through Table 6. If parameters similar to those adopted by western courtiers in similar climate conditions were used for DER in China, this would result in a greater energy use reduction in all climates.

High levels of energy use reduction using core technology bundles along with improvements in indoor climate and thermal comfort can be only achieved when a DER adopts a quality assurance process, which in addition to design, construction, commissioning, and post-occupancy phases, includes formulation of clear and concise documentation of the owner's goals, expectations, and requirements for the renovated building during development of the statement of work. Another important component of the QA process is a procurement phase, during which bidders' qualifications, their understanding of the SOW and its requirements, and their previous experience are analyzed.

The key to making a DER cost effective is to time the retrofit as part of a major building renovation that already has allocated funds, including those required to meet minimum energy requirements. Because there is an overlap between the funds allocated for the retrofit and those required for the DER, achieving the DER requires only an incremental cost, because the DER is evaluated based on a bundle of core technologies, not on individual energy efficiency measures. Some core technologies (e.g., those related to building envelope insulation and replacement of windows), which may not be cost effective when implemented individually, become economically attractive when implemented in a technology bundle. Implementation of these technologies can significantly reduce building heating and cooling loads and consequently reduce the size and cost of HVAC mechanical equipment, which subsequently results in reduced annual maintenance and insurance costs for these systems.

A DER that results in improved building energy efficiency (reduced energy bills), better indoor air quality, and thermal comfort provides significant added value in terms of improved "leasability" and immediate financial return (i.e., higher rent). Also, many DER projects actually increase a building's rentable/usable space (e.g., by reducing the size of mechanical rooms, adding thermally controlled areas [mansards, basements, and repurposing storage spaces]), which can be accounted for in the estimation of the rentable space revenues. For more objective understanding of DER economics, these factors need to be accounted for in the project LCC analysis.

The paper proposes a new method of evaluation of maximum allowable (LCC effective) budget increase for additional energy use reducing technical measures (compared to the available budget for major renovation). The method is based on scalar ratios to be used for the reduction in operating costs and increased revenues discussed above. The real budget required for a DER may depend on many factors, including the state of the national or local economy, local labor costs, the local and national system of energy-related incentives available at the time of the project, the availability and prices of specific energy efficient technologies, familiarity and experience of contractors with DER projects, and contracting mechanisms used. When a DER is cost effective, additional funding can become available either from the government or public funds or from the private funding sources (using energy savings performance contract [ESPC] or utility energy service contract (UESC) models) (Zhivov et al. 2015).

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