COMBINING BUILDING RENOVATION AND GROUND SOURCE HEAT PUMP INSTALLATIONS FOR THE REDUCTION OF GREENHOUSE GAS EMISSIONS: A Case Study in Vaasa Finland

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ABSTRACT

Given the growing interest in ground source heat pump and distributed heating installations in general for the reduction of greenhouse gas emissions, technology implementation planning can benefit from the simultaneous consideration of building renovations. Here, a method for identifying and evaluating scenarios based on cost and greenhouse gas emissions is presented. The method is demonstrated for a case study in Vaasa Finland. The case study considers the insulation of the walls, roof, and base floor and the replacement of windows based on 2003 and 2010 Finnish building codes simultaneously with the possible replacement of existing heat sources with ground source heat pumps. Estimates of changes in heat demand for consecutive renovations are combined with data on renovation, installation, heating costs, and life cycle greenhouse gas emissions data for the current and proposed heat sources. Preferred scenarios are identified and evaluated by building type, construction decade, and current heating source. The results are then placed within the contexts of the Vaasa building stock and policy theory.

KEY WORDS

sustainable buildings, greenhouse gases, technology implementation, life cycle assessment, life cycle costing, renovation, distributed energy, ground source heat

1. INTRODUCTION

A recent Intergovernmental Panel on Climate Change (IPCC) synthesis report suggests that measures to reduce GHG emissions from buildings fall into one of three categories: reducing energy consumption and embodied energy in buildings, switching to low-carbon fuels including a higher share of renewable energy, or controlling the emissions of non-CO_2 GHG gases [1]. They however divide the building-sector relevant technology assessments in two: presenting information for energy efficiency in new and existing buildings (**demand-side** building GHG reduction technologies) separate from their assessment of centralized and decentralized (or distributed) energy systems (**supply-side** GHG reduction technologies). Since building sector decision makers can influence both demand and supply side technology adoption, simultaneous consideration of tradeoffs made at the building (e.g., by architects, those in construction, etc.) and regional levels (e.g., by policy developers) is warranted.

Whereas some building technologies will be effective irrespective of the installation location (e.g., use of energy efficient lighting and appliances on the demand side), the effectiveness of other technologies is site specific. Table 1 lists example demand and supply-side building technologies with performance that depend on the regional ecosystem or the local infrastructure (modified and extended from [2]). Here, the performance parameters influence how much energy is demanded or supplied given implementation in a specific region and subsequently the GHG profile.

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TABLE 1. Example regional or site specific performance parameters for building technologies for GHG emissions reduction

	Example Building Technologies	Performance parameters that depend on the regional ecosystem or local infrastructure
DEMAND-SIDE TECHNOLOGIES for reducing energy demand, not including lights and appliances	Heating, ventilation and air conditioning (HVAC) and thermal distribution technologies (e.g., desiccant preconditioners for ventilation air; displacement ventilation; and passive solar heating)	Seasonal temperatures and solar radiation, humidity levels, hours of daylight/ latitude
	Insulation and leakage reduction for roofs, facade, floors, and basements (e.g., high-thermal-resistant foam insulations; structurally reinforced beaded vacuum panels; self-drying wall and roof designs; switchable evacuated panels; vacuum powder-filled, gas-filled, vacuum fiber-filled panels)	
	Lighting technologies (e.g., daylighting and light tubes)	
	Thermal storage materials (e.g., dry phase-change materials; encapsulated materials)	
	Window systems (e.g., krypton-filled, triple-glazed, low-E windows; electrochromic glazing; hybrid electrochromic/ photovoltaic films and coatings)	
	Heat island technologies (tree plantings; reflective roof products such as coatings and single-ply materials, tiles, shingles, and membranes; cool pavements)	
SUPPLY-SIDE TECHNOLOGIES On-site energy and power and with examples primarily focused on those suited for distributed systems	Biomass-fueled electricity and/or heating (with fire places, boilers, turbines, microturbines, reciprocating engines, stirling engines, fuel cells)	Biomass type; biomass moisture content; seasonal biomass availability; distance from source to processing; distance from processing to use
	Carbon dioxide capture	Geologic formation (for some options)
	Fuel cells (natural gas, propane, liquid or gaseous hydrogen, fuel oil, diesel)	Fuel constituents; fuel access (pipeline or pipeline + other transport)
	Ground source heat pumps	Soil type; seasonal temperatures; land area available
	Microturbines (on natural gas, hydrogen, propane, diesel)	Fuel constituents, fuel access (pipeline or pipeline + other transport)
	Solar technologies: building integrated photovoltaics; solar thermal electric power plants; solar power towers; parabolic troughs; concentrating collectors; solar updraft tower; solar pond; solar air and water heating	Annual solar radiation (tilted surface); annual average temperature; annual average wind speed (often modeled by latitude); land area available
	Small hydro	Water access/ area; gross head (drop in elevation at the site); maximum tailwater effect; residual flow; firm flow
	Wind systems	Annual average wind speed; wind power density; wind shear exponent; average atmospheric pressure; annual average temperature; land area available
	Hybrid systems	Combinations of those listed above

In addition to regional differences in technology performance, understanding GHG mitigation potential must also include life cycle considerations. Here, the life cycle is defined to extend from the acquisition and processing of feedstocks and construction materials (e.g., crude oil extraction, mining, agriculture) through the construction, renovation, operation, maintenance, and retirement of buildings and building technologies. Our hypothesis is that priorities for GHG emissions reduction can only be identified by *simultaneously considering* (1) regional variations in technology performance, (2) regional differences in the use of energy production technologies, and (3) life cycle environmental and economic implications of implementation. Herein, we investigate data and computational needs to test our hypothesis by developing and assessment of un-renovated buildings in Vaasa, a municipality on the west coast of Finland. Our case study is limited to the consideration of select costs, fuel life cycle GHG emissions, select renovation scenarios, and the possible replacement of existing heat sources with GSHPs. GSHPs were chosen due to the growing popularity of this distributed energy technology with annual unit sales increasing tenfold in several nations of Europe and Scandinavia over the past decade [3]. A GSHP, as described by Natural Resources Canada [4], leverages the low thermal conductivity of the ground, ground water, or surface water so that heat stored during the summer may be accessed during the winter (to provide heat for buildings) and the cooler conditions of winter may be accessed during the summer (to provide cooling for buildings). "Closed loop" GSHP systems make the connection to the ground, ground water, or surface water through buried or submerged pipes or tubing moving an antifreeze fluid (e.g., water or another heat-transfer fluid) from a heat pump, around the tubing, and back to the heat pump. Alternatively, "open loop" systems draw water from a well or surface water, transfer heat to or from the water, and then return it to the water source. In general, GSHP systems produce more energy than they use, with efficiencies routinely averaging 200 to 500% over a season. Herein, we consider vertical, horizontal, and groundwater GSHP systems as described by Natural Resources Canada.

2. EXTENDING PREVIOUS WORKS

Both costs and life cycle environmental impacts are increasingly considered in building technology assessments. Specifically, example Life Cycle Assessments (LCAs) cover a variety of building materials [5–8] as well as residential heating and cooling systems based on regional characterizations [9, 10]. Among these studies, only Papaefthimiou, et al. [7] combine LCA and cost assessment in an evaluation of advanced window glazing technologies aimed at the development of a rating scheme that can be useful for the consumers and product manufacturers to prioritize implementation strategies. Although not including LCA, other researchers have also prioritized implementation strategies considering a wider range of technology options and costs. For example, Papadopoulos, et al. [11] evaluate discrete choices among fuels and heating systems and Hong, et al. [12] estimate an optimal U-value or insulation thickness. However, fewer studies simultaneously consider priorities for alternatives on both sides of supply (as in renovation options) and demand (as in a change in the energy source). Select technology studies present chapters on individual technologies but do not offer simultaneous consideration of technologies within or between the supply and demand sides (notable examples include [13, 14]). Exceptions include Hasan, et al. [15] who use insulation thickness as a continuous variable and window replacement and heat recovery as discrete variables and Boermans, et al. [16] who assess the role of insulation and window and boiler replacements. Also, the US Department of Energy National Renewable Energy Laboratories (NREL) BeOpt software (see Christensen, et al. [17] and Anderson, et al. [18]) considers net-metered photovoltaic and active solar systems in combination with discrete building construction options with a goal of identifying zero energy solutions.

Christensen, et al., Hasan, et al., and Boermans, et al. define improvement strategies by presenting cost as a function of the demand for heat (as kW per floor or component area per year). These studies, and as depicted in Figure 1a, assume building components are successively installed at some cost and offer successively increasing reductions from a baseline heat demand, the form of the annual heat demand

FIGURE 1. Minimum cost scenarios based on annual heat demand, cost and GHG emissions.

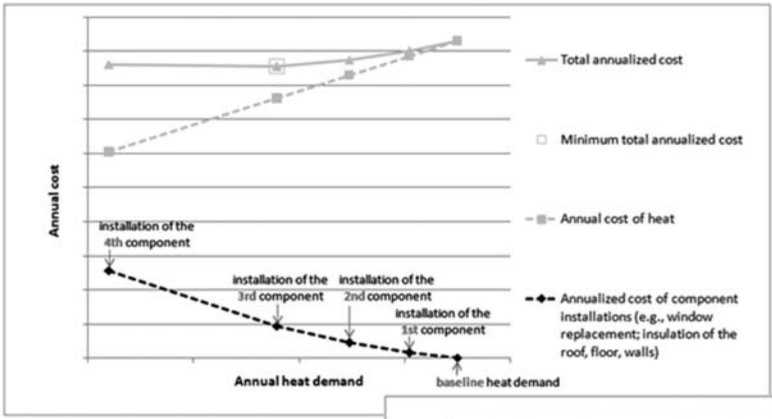


Figure 1a: Successively installed building components offer successively increasing reductions from a baseline heat demand

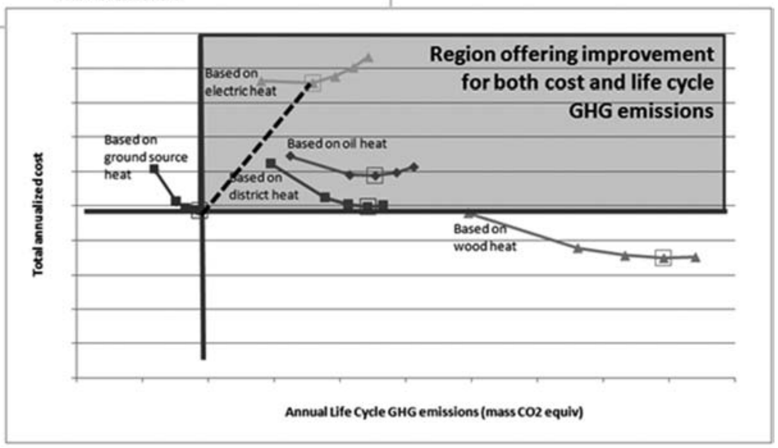


Figure 1b: When differences in life cycle GHG emissions are considered by heat generation source, the curve for same renovation scenario may or may not reside within a region offering improvement for both LCC and life cycle GHG emissions

vs. the annualized cost of component installation curve follows a negative slope (as well demonstrated by Christensen, et al. and Hasan, et al.). Assuming the cost of heat combines a fixed fee (which can be zero or non-zero) with a fee based on the amount of heat consumed, the annual heat demand vs. annual cost of heat follows a positive slope (as well demonstrated by Christensen, et al. and Boermans, et al.). Combing the installation and heat cost components into a "total annualized cost" allows a minimum cost to be identified (as in the work of Christensen, et al., Hasan, et al. and Boermans, et al.), with the possible minimum-cost scenario anywhere on the curve from the baseline option to the execution of all heat reduction options. In Figure 1a, the cost minimum occurs given the installation of the first, second, and third components, such that although the installation of the fourth component would offer further reduction of the demand for heat, it would come at a total annualized cost that is higher than that offered by the previous installations.

Although not described by Christensen, et al., Hasan, et al., and Boermans, et al., when renovation priorities also consider the existing heat source, whereas the annualized cost of renovations relationships remain as in Figure 1a, because the cost and environmental impact varies by heat source, different preferred scenarios are revealed. As shown in Figure 1b, replacing the heat demand on the X-axis with the life cycle GHG emissions, for example, keeps the cost minimum for each heat source at the same renovation scenario but compresses or spreads the total cost curve depending upon the GHG emissions per unit of heat delivered, resulting in a graphical region offering improvement for both cost and GHG emissions.

This formulation can be useful in determining promising application of distributed energy technologies for existing buildings. In Figure 1b, and using GSHPs as an example distributed energy technology, if the heat source is technologies 1 or 2, considering a change to GSHP without any renovation is the minimum cost option and offers substantial GHG emissions reduction (they fall squarely within the region offering improvement). For technology 3 and still within the region offering improvement, the 1st renovation option with no switch to a GSHP is approximately equivalent to a GSHP installation with no renovation at the lowest cost point, with the switch to GSHP offering substantial GHG emissions reduction. For technology 4, the 1st renovation option with no switch to GSHP is the low cost option, but switching to GSHP will substantially reduce GHG emissions at an increased cost, with technology 4 falling outside the region offering improvement for both cost and GHG emissions. Thus, in Figure 1b, whereas the switch to GSHPs is an improvement on cost and GHG emissions for the test case building if it is using technologies 1 and 2, the benefits are less obvious for those currently using technologies 3 and 4.

Further, considering just the two dimensions (annual cost and annual GHG emissions) presented in Figure 1b, a way to prioritize implementation scenarios is to balance the proposed changes in annual cost and changes in annual GHG emissions. Essentially, such a balance can be represented by the length of the dotted line in Figure 1b: as long as the proposed scenario falls within the region offering improvemet, the longer the line, the higher the priority for implementation. Although presented here considering just these two dimensions, extension to a large number of performance indicators is described in the discussion.

For our two dimensions, we develop data and assess example renovation and distributed generation installation scenarios following Figures 1a and 1b and assuming that the reduction of GHG emissions is desired given consideration of the cost of renovations and the cost of heat. Our case study moves from the estimation of heat demand, to the estimation of operating costs and fuel life cycle GHG emissions, and finally to an evaluation of priority renovation and GSHP implementation strategies for Vaasa, Finland.

3. CASE STUDY IN VAASA, FINLAND

3.1. Estimation of the demand for heat

On the basis of building statistics, we first classified Vaasa's residential buildings into 72 classes as detached, attached, and multistory buildings by construction decade in a manner similar to Petersdorff, et al. [19, 20] and Hong, et al. [12]. The characteristics of the buildings used in our case study are presented in Table 2 by construction decade. The characteristics are the floor area, the building volume, the number of stories and the story height, and length-to-width ratio of the building footprint.

We next estimated the heat demand as a function of construction decade building codes. We started with estimates of the areas of exterior walls, the roof, the base floor and all windows for each building class for each construction decade as presented in Table 3. The associated U-values are presented in Table 4 for the current situation based on building codes by construction decade and for the proposed renovations to 2003 and 2010 building codes. Based on these data, we used WinEntana [21], a tool designed for energy assessments of Finnish buildings, to estimate the heat demand by Vaasa un-renovated buildings. Estimates included heat for space and water heating as well as appliance and real estate electricity. WinEntana includes data for building configurations based on building codes during the year of construction. The estimated heat demand results are presented in Table 5. Next, the estimated space heat reductions were partitioned among each of the building components on the bases of the changes in U-values and the assumed component areas as presented in Table 6 and summarized in Figure 2.

3.2. Estimation of GHG emissions and costs

Due to a lack of readily available on the life cycles of materials used in equipment construction and maintenance for Finland, our estimation of GHG

TABLE 2. Vaasa un-renovated building characteristics.

	Building Class	Floor Area (m^2/ building)	Volume (m^3/ building)	Story Height	Number of Stories	X/Y Ratio for Assumed Rectangular Building Footprint
–1959	Detached	123	346	2.8	1	0.63
	Attached	361	1,010	2.8	2	0.25
	Multistory	690	1,931	2.8	4	0.50
1960–1969	Detached	143	401	2.8	1	0.63
	Attached	784	2,194	2.8	2	0.25
	Multistory	2,081	5,826	2.8	4	0.50
1970–1979	Detached	165	463	2.8	1	0.63
	Attached	545	1,635	3.0	2	0.25
	Multistory	1,724	5,171	3.0	4	0.50
1980–1989	Detached	174	488	2.8	1	0.63
	Attached	429	1,288	3.0	2	0.25
	Multistory	1,414	4,526	3.2	4	0.50
1990–1999	Detached	181	543	3.0	1	0.63
	Attached	401	1,202	3.0	2	0.25
	Multistory	1,020	3,264	3.2	4	0.50
2000+	Detached	183	550	3.0	1	0.63
	Attached	463	1,388	3.0	2	0.25
	Multistory	1,092	3,712	3.4	4	0.50

emissions was limited to the fuel life cycle, from resource acquisition through fuel use. Given this, the fuel life cycle GHG emissions for each heat source were measured in "kg CO_2 equivalents/ kWh" as 0.28, 0.25, 0.52, 0.26, 0.10, 0.11, and 0.11 for oil, electric, wood/peat, district, and vertical, horizontal, and groundwater GSHP systems respectively. These data were in part based on previous LCA research. Specifically, life cycle electricity and district heat GHG data were used as presented by Häkkinen, et al. [22]. Estimates for life cycle oil and wood/peat heat were based on data provided by Tattari [23] with the additional assumption that 58% of the carbon dioxide (CO_2) emissions attributed to renewable energy generation for wood/peat heat was sequestered during biomass growth. Although this value is intended to account for carbon uptake during biomass growth (i.e., based on uptake during photosynthesis), it does not account for the impact of land use changes or disturbances.

GSHP electricity demand was estimated using the RETScreen model developed by Natural Resources Canada [4] combined with the system size estimated based on data from WinEntana [21] and resulting in the use of a fixed relationship relating the heating system power (in kW) to 0.33 times the annual heating demand (in MWh) based on a R^2 of 0.99 (i.e., kW power = 0.33 × MWh annual heat demand). The RETScreen model calculates the electricity used by the GSHPs to meet heating and cooling requirements of a building. For horizontal and vertical systems, the electricity used includes that for the heat and circulating pumps. For groundwater heat pump systems, the electricity used also includes that needed for building loop circulating pumps and the electric energy required for water well pumps. In all cases, circulating pump power is assumed to be 17 W for each 1,000 W of capacity used by the heat pump system [4]. Figure 3 presents the estimated electricity demand for each of the 3 RETScreen heat pumps and the modeling as-

TABLE 3. Building component areas.

Construction decade	Building Class	Building Component Areas (m^2)			
		Walls	roof	base floor	all windows
–1959	Detached	111	124	124	17
	Attached	334	180	180	42
	Multistory	543	172	172	81
1960–1969	Detached	118	143	143	19
	Attached	463	392	392	92
	Multistory	840	520	437	243
1970–1979	Detached	129	165	165	19
	Attached	431	273	273	64
	Multistory	855	431	384	202
1980–1989	Detached	131	174	174	20
	Attached	389	215	215	50
	Multistory	856	354	335	165
1990–1999	Detached	145	181	181	21
	Attached	378	200	200	47
	Multistory	748	255	255	119
2000+	Detached	145	183	183	21
	Attached	402	231	231	54
	Multistory	826	273	273	128

TABLE 4. Case study U-values.

	U-values (W/m^2,K)			
	walls	roof	base floor	all windows
un-renovated buildings constructed in1959 or earlier	0.6	0.39	0.48	2.2
un-renovated buildings constructed between 1960–1969	0.475	0.335	0.48	2.2
un-renovated buildings constructed between 1970–1979	0.32	0.26	0.40	1.8
un-renovated buildings constructed between 1980–1989	0.28	0.22	0.36	1.8
un-renovated buildings constructed between 1990–1999	0.28	0.22	0.36	1.8
un-renovated buildings constructed from 2000 and beyond	0.25	0.16	0.25	1.4
renovation to 2003 building codes	0.25	0.16	0.20	1.4
renovation to 2010 building codes	0.15	0.10	0.12	0.70

sumptions applied, such that the fuel life cycle GHG emissions can then be based on electricity consumed. Again, system construction and maintenance as well as refrigerant loss were not considered and only life cycle CO_2, methane, and nitrous oxide emissions were included in the LCAs. Finally, 100-year Global Warming Potentials (GWPs) of 1, 25, and 298 CO_2 equivalents/kg-emitted were assumed for CO_2, methane, and nitrous oxide respectively as defined by the IPCC [24].

TABLE 5. Estimated heat demand per building.

Construction decade	Building Class	Water Heating Demand (kWh/year)	Space Heating Demand (kWh/year)		
			Un-renovated	renovation to 2003 building codes	renovation to 2010 building codes
–1959	Detached	1.46E+03	2.72E+04	1.24E+04	7.21E+03
	Attached	1.73E+04	7.27E+04	3.97E+04	2.85E+04
	Multistory	3.31E+04	1.18E+05	6.83E+04	5.08E+04
1960–1969	Detached	1.69E+03	2.79E+04	1.43E+04	8.40E+03
	Attached	3.76E+04	1.27E+05	7.88E+04	5.83E+04
	Multistory	9.98E+04	2.76E+05	1.84E+05	1.43E+05
1970–1979	Detached	1.95E+03	2.72E+04	1.63E+04	9.69E+03
	Attached	2.80E+04	8.90E+04	6.07E+04	4.45E+04
	Multistory	8.86E+04	2.38E+05	1.66E+05	1.28E+05
1980–1989	Detached	2.06E+03	2.66E+04	1.71E+04	1.02E+04
	Attached	2.21E+04	6.88E+04	4.94E+04	3.59E+04
	Multistory	7.76E+04	2.04E+05	1.48E+05	1.14E+05
1990–1999	Detached	2.29E+03	2.56E+04	1.87E+04	1.13E+04
	Attached	2.06E+04	5.75E+04	4.63E+04	3.35E+04
	Multistory	5.59E+04	1.34E+05	1.10E+05	8.36E+04
2000+	Detached	2.32E+03	1.94E+04	1.89E+04	1.14E+04
	Attached	2.38E+04	5.34E+04	5.29E+04	3.85E+04
	Multistory	6.36E+04	1.38E+05	1.24E+05	9.49E+04

For the cost of renovations, we assumed installation costs of 90, 30, 50, and 65 €/m^2 structure for renovation to 2003 building codes and 230, 70, 130, 140 €/m^2 structure for renovation to 2010 building codes for the walls, roof, base floor, and windows respectively. The installation costs were based on an informal survey of insulation and window suppliers and contractors in Finland and used to estimate annualized installation costs, presented in Table 7. Costs were annualized to match the annual assessment of GHG emissions and assuming an escalation of 2.5% over 25 years. Note that the costs of funding and renewing were not included.

Finally, the cost of heat for buildings was assumed to be 0.068, 0.099, and 0.039 €/kWh for oil, electric, and wood/peat with district heat costs at 0.044, 0.041, and 0.039 €/kWh for detached, attached, and multistory buildings. Also, an annual cost per residence of 144 and 471 €/kWh was added for electric and district heating systems respectively. This left ground source heat costs based on the electricity consumption (at 0.099 €/kWh) without an annual residence cost. These heating costs are based on data from Eurostat and Helsingin Sanomat [25].

3.3. Identification of the minimum-operating-cost options

The minimum operating cost options for the Vaasa buildings are listed in Table 8 by heat source, building type, and construction decade. The costs were estimated (a) with and without each type of GSHP installation and (b) such that renovation technologies (insulation of the walls, roof, or base floor, or replacement of all windows) would be consecutively installed. We defined consecutive installation as a set of renovation sequences starting with the renovation option with the minimum install cost/kWh of heat demand reduced (based on data from Table 6 and

TABLE 6. Estimated space heat *reduction* by building component (kWh/year per building).

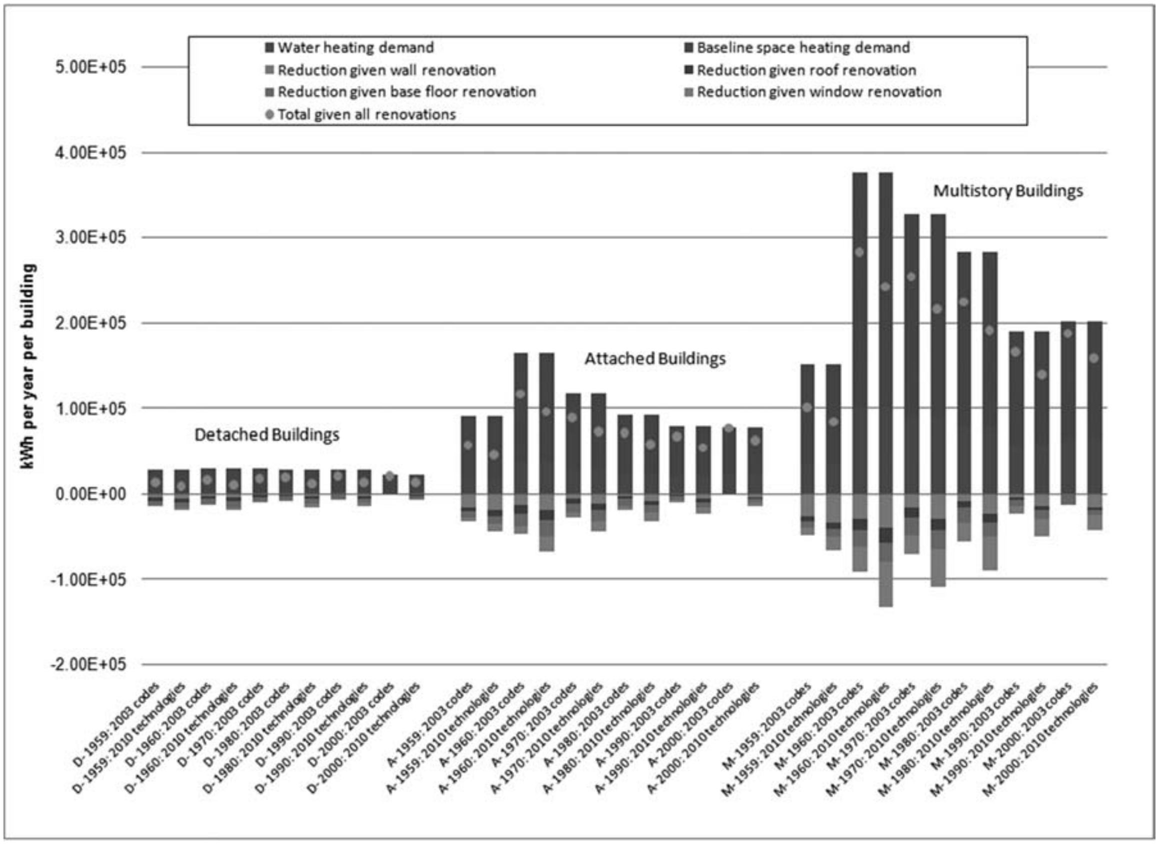
Construction decade	Building Class	renovation to 2003 building codes				renovation to 2010 building codes			
		wall	roof	base floor	all windows	wall	roof	base floor	all windows
–1959	Detached	4.98E+03	3.64E+03	4.43E+03	1.71E+03	6.43E+03	4.60E+03	5.72E+03	3.21E+03
	Attached	1.59E+04	5.64E+03	6.87E+03	4.59E+03	2.01E+04	6.99E+03	8.67E+03	8.46E+03
	Multistory	2.76E+04	5.75E+03	7.00E+03	9.36E+03	3.44E+04	7.04E+03	8.74E+03	1.70E+04
1960–1969	Detached	3.37E+03	3.17E+03	5.08E+03	1.96E+03	4.91E+03	4.30E+03	6.59E+03	3.71E+03
	Attached	1.41E+04	9.27E+03	1.48E+04	9.92E+03	1.98E+04	1.21E+04	1.86E+04	1.81E+04
	Multistory	2.92E+04	1.41E+04	1.89E+04	3.01E+04	3.97E+04	1.78E+04	2.29E+04	5.31E+04
1970–1979	Detached	1.48E+03	2.72E+03	5.44E+03	1.27E+03	3.30E+03	4.00E+03	7.00E+03	3.21E+03
	Attached	6.22E+03	5.61E+03	1.12E+04	5.25E+03	1.24E+04	7.36E+03	1.29E+04	1.18E+04
	Multistory	1.64E+04	1.18E+04	2.11E+04	2.22E+04	2.92E+04	1.39E+04	2.16E+04	4.46E+04
1980–1989	Detached	7.37E+02	1.95E+03	5.21E+03	1.53E+03	2.73E+03	3.34E+03	6.68E+03	3.58E+03
	Attached	2.87E+03	3.16E+03	8.43E+03	4.93E+03	9.10E+03	4.63E+03	9.26E+03	9.93E+03
	Multistory	8.75E+03	7.23E+03	1.82E+04	2.26E+04	2.43E+04	9.25E+03	1.75E+04	3.97E+04
1990–1999	Detached	5.69E+02	1.42E+03	3.80E+03	1.11E+03	2.51E+03	2.90E+03	5.80E+03	3.11E+03
	Attached	1.70E+03	1.81E+03	4.82E+03	2.82E+03	6.79E+03	3.33E+03	6.65E+03	7.14E+03
	Multistory	4.19E+03	2.86E+03	7.62E+03	8.91E+03	1.52E+04	4.78E+03	9.55E+03	2.05E+04
2000+	Detached	0.00E+00	0.00E+00	4.77E+02	0.00E+00	1.80E+03	1.36E+03	2.95E+03	1.86E+03
	Attached	0.00E+00	0.00E+00	5.21E+02	0.00E+00	4.90E+03	1.69E+03	3.66E+03	4.62E+03
	Multistory	0.00E+00	0.00E+00	1.37E+04	0.00E+00	1.58E+04	3.14E+03	6.80E+03	1.71E+04

Table 7), assuming that only one renovation option could be applied per building component (i.e., either the component was updated to the 2003 or the 2010 building codes), and subsequently comprised of technologies with lowest install cost/kWh of heat demand reduced for each successive component. As expected, it is found that the building components are successively installed at some cost and offer successively increasing reductions from a baseline heat demand, following the graphical form depicted in Figures 1a and 1b. Also all types of GSHPs are considered in each cell of Table 8, resulting in some instances in which a certain type of GSHP is preferred or a certain renovation scenario is preferred. For example, for attached buildings using electricity and built between 1970 and 1979, whereas the minimum operating cost option for vertical GSHPs is installation without any renovation, the minimum option for horizontal and groundwater GSHP is not to install but instead to replace the windows to the 2010 building codes.

Inspection of Table 8 reveals at least two things. First, of the 72 building classes considered, only 5 types of minimum-operating cost options were identified: as-is (for 9 classes); 2003 window installation only (for 9 classes), any GSHP (for 24 classes); any GSHP plus 2003 windows (for 27 classes); and vGSHP, hGSHP or gGSHP plus 2010 windows (for 3 classes). Second, GSHPs are never found herein to offer the minimum cost option for buildings currently using wood heat. This is because the cost of wood heat remains below the cost of the electricity estimated to be used for potential GSHP installations.

Next, the renovation sequences and the heating demands resulting from the consecutive installations modeled are presented in Table 9, assuming no change in the water heating demand will occur. For the results in both Table 8 and Table 9, replacement of the current heating source by GSHPs was assumed to apply to all systems, which in some cases would necessitate the use of multiple heat pumps

FIGURE 2. Renovation improvement option performance.



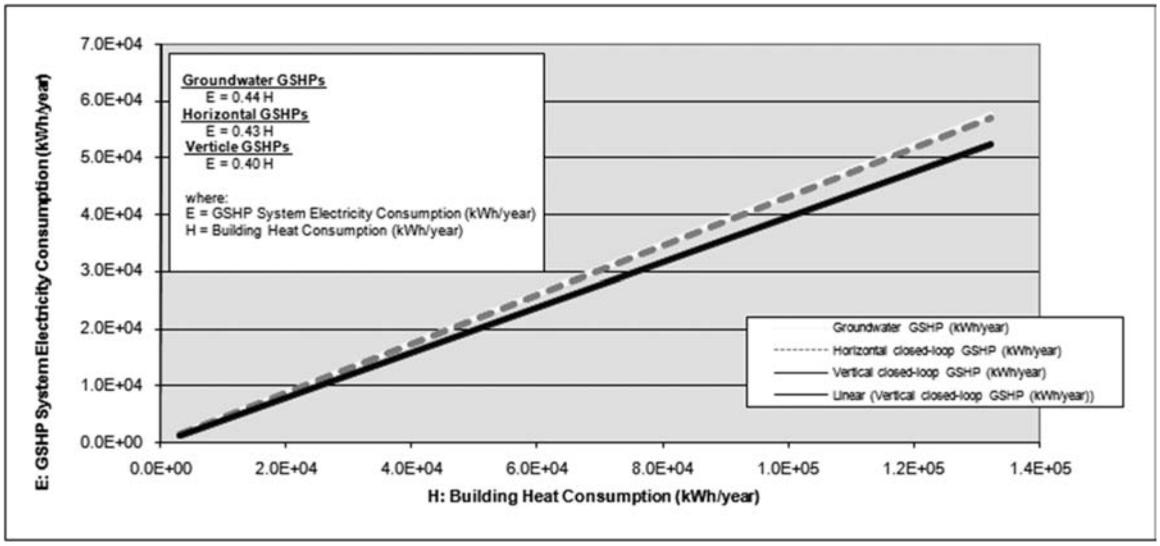
(for systems requiring more than 35kW or ~105,000 kWh/year) to match current equipment availability [4]. Instances in which multiple units would be required are denoted in Table 9 with a ►. In fact, single units are estimated to never apply to multistory buildings constructed after 1960. Alternatively, for multistory buildings constructed before 1960 and attached buildings constructed between 1970 and 1979, renovations were estimated to make the buildings candidates for single GSHP units whereas they were not in the baseline condition.

Also, the raw results are presented by building class in Table 10 summarized by heat source, building type, and construction year) and in Table 11 for each of the 72 building classes. As shown, on both an individual building and stock basis, buildings currently using electric heat, multistory buildings, and buildings constructed before 1959 offer the greatest potential reductions in cost and GHG emissions in their respective subcategories.

3.4. Evaluation of the minimum-operating-cost options

From a policy standpoint, an opportunity exists for Vaasa to consider facilitating/ providing resources for building renovations and the installations of GSHPs for reductions in GHG emissions and using knowledge of minimum operating costs. For example, the municipality might be interested in developing plans to address the 2006 European Commission Action Plan on Energy Efficiency, with a goal of a 20% emissions reduction target for greenhouse gases by 2020 [26]. To assess this target, we next estimated the number of candidate un-renovated

FIGURE 3. Electricity demand by GSHPs in Vaasa.



RETScreen Model Parameters	
Heating design temperature (ºC)	–16.5
Cooling design temperature (ºC)	17.5
Average summer daily temperature range (ºC)	5.31
Cooling humidity level	Medium
Latitude of project location	63.1
Mean earth temperature (ºC)	1.28
Annual earth temperature amplitude (ºC)	22.2
Soil types investigated	Heavy rock, light rock, damp heavy soil, dry heavy soil, damp light soil, dry light soil
Design heating load (kW)	Varied from 5 to 45 kW
Annual heating energy demand (MWh)	MWh = kW/0.33 (from [21])

Vaasa buildings, characterized their current fuel life cycle GHG emissions by heat source, and estimated the impacts of minimum-operating-cost option implementation.

To this end, we assumed that although many of the buildings constructed in Vaasa before 1970 have already been renovated, these renovations were not intended to reduce the demand for heat. We based this assumption on two studies. First, Vainio, et al. [27] described a large share of facade renovations, typically either cladding or painting. Second, Holopainen et al. [28] noted that in most of the older buildings, windows are either renewed or repaired as opposed to replaced. Thus, here we assume that the number of buildings already renovated (in terms of significantly improved energy-efficiency) is very low, at 5% for buildings constructed 1969 and before and at 0% thereafter. Data for the total number of buildings in each class was obtained from Statistics Finland [29], with the number considered un-renovated and the number of apartments listed in Table 12.

To estimate the fuel life cycle GHG emissions from the Vaasa un-renovated stock, we first estimated the percent of each building class using each of 5 heat sources. The data used are presented in Table 13, which follow both the trends shown in Vehviläinen et al. [30] and in Ostrabotnia statistics provided by Statistics Finland [29, 31]. Next,

TABLE 7. Estimated annual installation cost by building component (€/year/ building).

Construction decade	Building Class	renovation to 2003 building codes				renovation to 2010 building codes			
		wall	roof	base floor	all windows	wall	roof	base floor	all windows
–1959	Detached	5.43E+02	2.01E+02	3.35E+02	5.88E+01	1.39E+03	4.69E+02	8.72E+02	1.27E+02
	Attached	1.59E+04	5.64E+03	6.87E+03	4.59E+03	2.01E+04	6.99E+03	8.67E+03	8.46E+03
	Multistory	2.76E+04	5.75E+03	7.00E+03	9.36E+03	3.44E+04	7.04E+03	8.74E+03	1.70E+04
1960–1969	Detached	5.78E+02	2.33E+02	3.89E+02	6.82E+01	1.48E+03	5.44E+02	1.01E+03	1.47E+02
	Attached	1.41E+04	9.27E+03	1.48E+04	9.92E+03	1.98E+04	1.21E+04	1.86E+04	1.81E+04
	Multistory	2.92E+04	1.41E+04	1.89E+04	3.01E+04	3.97E+04	1.78E+04	2.29E+04	5.31E+04
1970–1979	Detached	6.28E+02	2.69E+02	4.49E+02	6.82E+01	1.60E+03	6.28E+02	1.17E+03	1.47E+02
	Attached	6.22E+03	5.61E+03	1.12E+04	5.25E+03	1.24E+04	7.36E+03	1.29E+04	1.18E+04
	Multistory	1.64E+04	1.18E+04	2.11E+04	2.22E+04	2.92E+04	1.39E+04	2.16E+04	4.46E+04
1980–1989	Detached	6.42E+02	2.84E+02	4.73E+02	7.20E+01	1.64E+03	6.62E+02	1.23E+03	1.55E+02
	Attached	2.87E+03	3.16E+03	8.43E+03	4.93E+03	9.10E+03	4.63E+03	9.26E+03	9.93E+03
	Multistory	8.75E+03	7.23E+03	1.82E+04	2.26E+04	2.43E+04	9.25E+03	1.75E+04	3.97E+04
1990–1999	Detached	7.06E+02	2.95E+02	4.91E+02	7.47E+01	1.81E+03	6.88E+02	1.28E+03	1.61E+02
	Attached	1.70E+03	1.81E+03	4.82E+03	2.82E+03	6.79E+03	3.33E+03	6.65E+03	7.14E+03
	Multistory	4.19E+03	2.86E+03	7.62E+03	8.91E+03	1.52E+04	4.78E+03	9.55E+03	2.05E+04
2000+	Detached	7.10E+02	2.99E+02	4.98E+02	7.57E+01	1.81E+03	6.97E+02	1.29E+03	1.63E+02
	Attached	0.00E+00	0.00E+00	5.21E+02	0.00E+00	4.90E+03	1.69E+03	3.66E+03	4.62E+03
	Multistory	0.00E+00	0.00E+00	1.37E+04	0.00E+00	1.58E+04	3.14E+03	6.80E+03	1.71E+04

we estimated the fuel life cycle GHG emissions by heat source for the current and proposed minimum operating cost cases, as presented in Table 10 and Table 11. The resulting fuel life cycle GHG emissions for Vaasa for space and water heating totaled ~150Gg CO_2 equiv per year. Approximately 55% of these emissions comes from energy demand by multistory buildings with detached at ~37% and attached at ~9%. By construction class, the greatest emissions area associated with multistory buildings built between 1970 and 1979 and multistory and detached buildings built prior to 1959.

When comparing the current and proposed situations, we found that implementation of all the minimum-operating-cost-options has the potential for a ~11% reduction in fuel life cycle GHG emissions, thus missing the European Commission's reductions target of 20%. We did however re-estimate our results assuming, instead of implementation of the minimum-operating-cost options, that all renovations and GSHPs would be applied in all cases. This scenario resulted in a ~33% reduction, thus exceeding the European Commission's target.

Given these results, we were next interested in prioritizing the implementation options. Referring again to Figure 1b, because in Section 3.3 we maintained only options which offer cost improvement and because on a per kWh basis the fuel life cycle GSHP GHG emissions were estimated to be less than the current heating technologies, all of the proposed options fall within the improvement region. Thus, in order to prioritize the options, we estimated the length of the line from the current cost and GHG emissions point on a cost vs. emissions plot, essentially measuring the length of the hypotenuse of a triangle with sides with lengths representing each respective reduction. We then prioritized these results by assigning the longest line (the greatest combined difference between the cost and GHG reductions) a priority rank of 1, indicating that this option is the highest priority for implementation. Our priorities, based on

TABLE 8. Minimum operating cost options by heat source, building type, and construction decade.

Current source		1959	1960	1970	1980	1990	2000
oil	detached buildings	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP	Any GSHP	Any GSHP	Any GSHP
	attached buildings	Any GSHP + 2003 windows	Any GSHP + 2003 windows	vGSHP, hGSHP or gGSHP + 2010 windows	Any GSHP + 2003 windows	Any GSHP	Any GSHP
	multistory buildings	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP	Any GSHP
electric	detached buildings	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP	Any GSHP	Any GSHP	Any GSHP
	attached buildings	Any GSHP + 2003 windows	Any GSHP + 2003 windows	vGSHP, hGSHP or gGSHP + 2010 windows	Any GSHP + 2003 windows	Any GSHP	Any GSHP
	multistory buildings	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP	Any GSHP
wood	detached buildings	2003 windows	2003 windows	as-is	as-is	as-is	as-is
	attached buildings	2003 windows	2003 windows	as-is	2003 windows	as-is	as-is
	multistory buildings	2003 windows	2003 windows	2003 windows	2003 windows	as-is	as-is
district	detached buildings	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP	Any GSHP	Any GSHP	Any GSHP
	attached buildings	Any GSHP + 2003 windows	Any GSHP + 2003 windows	vGSHP, hGSHP or gGSHP + 2010 windows	Any GSHP + 2003 windows	Any GSHP	Any GSHP
	multistory buildings	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP + 2003 windows	Any GSHP	Any GSHP

the results for the un-renovated Vaasa stock, are presented in the last column of Table 11, finding that buildings currently using electric heat and built prior to 1960 and using oil heat and built in the 1970s and prior to 1959 top the list of Vaasa implementation priorities. Figure 4 presents the cumulative reductions based on this prioritization for the minimum-operating-cost options and for the scenarios in which all renovations and GSHPs would be applied in all cases.

TABLE 9. Renovation sequences and consecutive heating demand.

			1st renovation		2nd renovation		3rd renovation		4^{th} renovation	
		Baseline demand (kWh/year, including both space and water heating)	Technology with the minimum install cost/kWh of heat demand reduced	Heat demand given the 1st renovation	Technology, among the components remaining, with lowest install cost/ kWh of heat demand reduced	Heat demand given the 2nd renovation	Technology, among the components remaining, with lowest install cost/ kWh of heat demand reduced	Heat demand given the 3rd renovation	Technology, among the components remaining, with lowest install cost/ kWh of heat demand reduced	Heat demand given the 4th renovation
–1959	Detached	2.86E+4	2003 windows	2.69E+4	2003 roof	2.33E+4	2003 floor	1.89E+4	2003 wall	1.39E+4
	Attached	9.00E+4	2003 windows	8.54E+4	2003 roof	7.98E+4	2003 floor	7.29E+4	2003 wall	5.70E+4
	Multistory	1.51E+5 ►	2003 windows	1.42E+5 ►	2003 roof	1.36E+5 ►	2003 floor	1.29E+5 ►	2003 wall	1.01E+5
1960–1969	Detached	2.96E+4	2003 windows	2.76E+4	2003 roof	2.45E+4	2003 floor	1.94E+4	2003 wall	1.60E+4
	Attached	1.65E+5 ►	2003 windows	1.55E+5 ►	2003 roof	1.45E+5 ►	2003 floor	1.30E+5 ►	2003 wall	1.16E+5 ►
	Multistory	3.76E+5 ►	2003 windows	3.46E+5 ►	2003 roof	3.32E+5 ►	2003 floor	3.13E+5 ►	2003 wall	2.84E+5 ►
1970–1979	Detached	2.92E+4	2010 windows	2.59E+4	2003 floor	2.05E+4	2003 roof	1.78E+4	2003 wall	1.63E+4
	Attached	1.17E+5 ►	2010 windows	1.05E+5 ►	2003 floor	9.39E+4	2003 roof	8.83E+4	2003 wall	8.21E+4
	Multistory	3.26E+5 ►	2003 windows	3.04E+5 ►	2003 floor	2.83E+5 ►	2003 roof	2.71E+5 ►	2003 wall	2.55E+5 ►
1980–1989	Detached	2.86E+4	2010 windows	2.50E+4	2003 floor	1.98E+4	2003 roof	1.79E+4	2010 wall	1.51E+4
	Attached	9.09E+4	2003 windows	8.60E+4	2003 floor	7.75E+4	2003 roof	7.44E+4	2010 wall	6.53E+4
	Multistory	2.82E+5 ►	2003 windows	2.59E+5 ►	2003 floor	2.41E+5 ►	2003 roof	2.34E+5 ►	2010 wall	2.10E+5 ►
1990 - 1999	Detached	2.79E+4	2010 windows	2.48E+4	2003 floor	2.10E+4	2003 roof	1.96E+4	2010 wall	1.71E+4
	Attached	7.81E+4	2010 windows	7.09E+4	2003 floor	6.61E+4	2003 roof	6.43E+4	2010 wall	5.75E+4
	Multistory	1.90E+5 ►	2010 windows	1.69E+5 ►	2003 floor	1.61E+5 ►	2003 roof	1.59E+5 ►	2010 wall	1.43E+5 ►
2000+	Detached	2.17E+4	2010 windows	1.98E+4	2010 floor	1.69E+4	2010 roof	1.55E+4	2010 wall	1.37E+4
	Attached	7.72E+4	2010 windows	7.25E+4	2010 floor	6.89E+4	2010 roof	6.72E+4	2010 wall	6.23E+4
	Multistory	2.01E+5 ►	2003 floor	1.88E+5 ►	2010 windows	1.71E+5 ►	2010 roof	1.67E+5 ►	2010 wall	1.52E+5 ►

► Multiple GSHPs would be required

TABLE 10. Summary of costs and GHG emissions.

		For each building				For the un-renovated Vaasa stock				
		Current annual cost (€/year)	Proposed annual cost (€/year)	Current annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Proposed annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Current annual cost (€/year)	Proposed annual cost (€/year)	Current annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Proposed annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Subcategory priority
	Total	6.41E+5	6.14E+5	3.03E+6	2.75E+6	3.80E+7	3.64E+7	1.47E+8	1.31E+8	
Subtotal by heat source	Oil	1.57E+5	1.50E+5	6.56E+5	5.70E+5	1.04E+7	9.96E+6	4.36E+7	3.76E+7	2
	Electric	2.46E+5	2.27E+5	5.68E+5	4.63E+5	1.30E+7	1.20E+7	3.04E+7	2.34E+7	1
	Wood	9.01E+4	8.91E+4	1.21E+6	1.15E+6	1.45E+6	1.45E+6	1.94E+7	1.89E+7	4
	District	1.48E+5	1.47E+5	5.98E+5	5.66E+5	1.31E+7	1.30E+7	5.39E+7	5.08E+7	3
Subtotal by building type	Detached	4.51E+4	4.33E+4	2.17E+5	1.97E+5	1.23E+7	1.17E+7	5.44E+7	4.80E+7	2
	Attached	1.69E+5	1.64E+5	8.10E+5	7.50E+5	4.00E+6	3.82E+6	1.27E+7	1.13E+7	3
	Multistory	4.27E+5	4.07E+5	2.00E+6	1.80E+6	2.17E+7	2.09E+7	8.03E+7	7.14E+7	1
Subtotal by construction year	–1959	7.15E+4	6.80E+4	3.54E+5	3.12E+5	9.42E+6	8.91E+6	3.96E+7	3.39E+7	1
	1960–1969	1.58E+5	1.51E+5	7.47E+5	6.67E+5	6.08E+6	5.80E+6	2.28E+7	2.00E+7	4
	1970–1979	1.32E+5	1.25E+5	6.19E+5	5.52E+5	8.08E+6	7.72E+6	3.03E+7	2.66E+7	2
	1980–1989	1.12E+5	1.06E+5	5.26E+5	4.72E+5	7.23E+6	6.89E+6	2.73E+7	2.41E+7	3
	1990–1999	8.29E+4	8.05E+4	3.87E+5	3.69E+5	4.53E+6	4.41E+6	1.73E+7	1.63E+7	5
	2000+	8.48E+4	8.30E+4	3.94E+5	3.76E+5	2.69E+6	2.66E+6	1.02E+7	9.77E+6	6

Finally, it is important to note that since model development, the cost of heat has changed and can be expected to continue to change in Finland (and elsewhere). For example, the Finnish Forest Research Institute [32] states that in Finland in 2008 the cost of wood pellets was 0.035 €/kWh and the cost of oil was 0.040 €/kWh, thus at 10% and 41% variation on our assessed costs respectively. Thus, we investigated the impact of changes in energy cost to the top ten priorities found by varying the cost/kWh by +/–50% for each fuel as presented in Table 14. As shown, the top ten priorities remain intact for increases in the electricity cost and changes in the cost of wood/peat heat. However, the top ten priorities are found to change for other cost variations. Additions to the top ten are not beyond the top 26 out of the 72 building classes investigated. Of those that drop out of the top ten, the classes that drop match the cost that was reduced (e.g., a 50% reduction in the cost of oil results in the elimination of the 4 oil building classes from the top ten).

4. DISCUSSION

The methodology and case study presented here combine and assess concepts and procedures presented separately by other researchers. This includes the use of detailed computational models in the estimation of heat demand by construction decade and building class and for distributed energy technology performance that consider local conditions; the consideration of technological improvements on the supply and demand sides; and the use of life cycle environmental and cost. For the case study, the use of VTT's WinEntana for the estimation of heat demand giving consideration to local conditions and decade-specific building codes and Natural Resources Canada's

TABLE 11. Costs and GHG emissions by building class.

			For each building				For the un-renovated Vaasa stock				
			Current annual cost (€/year)	Proposed annual cost (€/year)	Current annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Proposed annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Current annual cost (€/year)	Proposed annual cost (€/year)	Current annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Proposed annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Option Priority
Oil	–1959	Det.	1.95E+3	1.84E+3	8.14E+3	6.62E+3	1.24E+6	1.18E+6	5.19E+6	4.22E+6	3
		Att.	6.12E+3	5.87E+3	2.56E+4	2.27E+4	4.86E+4	4.66E+4	2.03E+5	1.80E+5	45
		Mult	1.03E+4	9.81E+3	4.29E+4	3.67E+4	1.52E+6	1.45E+6	6.34E+6	5.41E+6	5
	1960–1969	Det.	2.01E+3	1.95E+3	8.41E+3	7.85E+3	3.74E+5	3.62E+5	1.56E+6	1.46E+6	33
		Att.	1.12E+4	1.08E+4	4.67E+4	4.39E+4	6.31E+4	6.11E+4	2.64E+5	2.48E+5	46
		Mult	2.56E+4	2.42E+4	1.07E+5	8.90E+4	1.23E+6	1.16E+6	5.15E+6	4.28E+6	6
	1970–1979	Det.	1.98E+3	1.91E+3	8.28E+3	7.37E+3	5.46E+5	5.27E+5	2.28E+6	2.03E+6	23
		Att.	7.95E+3	7.61E+3	3.32E+4	2.67E+4	1.45E+5	1.38E+5	6.04E+5	4.85E+5	31
		Mult	2.22E+4	2.09E+4	9.27E+4	7.70E+4	1.49E+6	1.40E+6	6.21E+6	5.16E+6	2
	1980–1989	Det.	1.95E+3	1.86E+3	8.13E+3	7.11E+3	6.37E+5	6.08E+5	2.66E+6	2.33E+6	19
		Att.	6.18E+3	6.02E+3	2.58E+4	2.44E+4	2.62E+5	2.56E+5	1.10E+6	1.04E+6	38
		Mult	1.92E+4	1.79E+4	8.01E+4	6.85E+4	9.83E+5	9.18E+5	4.11E+6	3.51E+6	12
	1990–1999	Det.	1.90E+3	1.85E+3	7.93E+3	7.05E+3	4.27E+5	4.15E+5	1.78E+6	1.58E+6	26
		Att.	5.31E+3	5.18E+3	2.22E+4	2.02E+4	7.32E+4	7.14E+4	3.06E+5	2.78E+5	43
		Mult	1.29E+4	1.24E+4	5.39E+4	4.81E+4	7.24E+5	6.96E+5	3.02E+6	2.70E+6	21
	2000+	Det.	1.47E+3	1.47E+3	6.16E+3	6.16E+3	3.18E+5	3.18E+5	1.33E+6	1.33E+6	51
		Att.	5.25E+3	5.25E+3	2.19E+4	2.19E+4	1.07E+5	1.07E+5	4.49E+5	4.49E+5	51
		Mult	1.37E+4	1.33E+4	5.72E+4	4.85E+4	2.58E+5	2.50E+5	1.08E+6	9.12E+5	29
Elect	–1959	Det.	2.98E+3	2.61E+3	7.04E+3	4.63E+3	1.84E+6	1.61E+6	4.34E+6	2.86E+6	1
		Att.	9.31E+3	8.55E+3	2.21E+4	1.79E+4	1.78E+5	1.64E+5	4.23E+5	3.43E+5	35
		Mult	1.56E+4	1.44E+4	3.71E+4	2.49E+4	1.23E+6	1.13E+6	2.92E+6	1.96E+6	4
	1960–1969	Det.	3.07E+3	2.75E+3	7.27E+3	4.77E+3	5.52E+5	4.94E+5	1.31E+6	8.55E+5	15
		Att.	1.72E+4	1.59E+4	4.04E+4	3.21E+4	2.34E+5	2.16E+5	5.50E+5	4.36E+5	32
		Mult	4.04E+4	3.71E+4	9.24E+4	7.69E+4	1.04E+6	9.52E+5	2.37E+6	1.98E+6	16
	1970–1979	Det.	3.03E+3	2.77E+3	7.16E+3	4.37E+3	8.07E+5	7.38E+5	1.91E+6	1.16E+6	7
		Att.	1.23E+4	1.11E+4	2.88E+4	2.17E+4	5.37E+5	4.86E+5	1.26E+6	9.51E+5	22
		Mult	3.51E+4	3.21E+4	8.02E+4	6.66E+4	1.25E+6	1.15E+6	2.86E+6	2.38E+6	14
	1980–1989	Det.	2.98E+3	2.73E+3	7.03E+3	4.87E+3	9.43E+5	8.66E+5	2.23E+6	1.54E+6	9
		Att.	9.65E+3	9.08E+3	2.23E+4	1.91E+4	9.86E+5	9.28E+5	2.28E+6	1.95E+6	18
		Mult	3.02E+4	2.75E+4	6.93E+4	5.75E+4	8.27E+5	7.54E+5	1.90E+6	1.57E+6	20
	1990–1999	Det.	2.91E+3	2.76E+3	6.86E+3	6.10E+3	6.32E+5	6.00E+5	1.49E+6	1.32E+6	28
		Att.	8.31E+3	7.96E+3	1.92E+4	1.74E+4	2.76E+5	2.65E+5	6.37E+5	5.79E+5	39
		Mult	2.04E+4	1.92E+4	4.66E+4	3.97E+4	6.12E+5	5.76E+5	1.40E+6	1.19E+6	24
	2000+	Det.	2.29E+3	2.27E+3	5.33E+3	4.87E+3	4.77E+5	4.73E+5	1.11E+6	1.02E+6	34
		Att.	8.27E+3	8.22E+3	1.90E+4	1.78E+4	4.08E+5	4.06E+5	9.36E+5	8.80E+5	40
		Mult	2.18E+4	2.04E+4	4.95E+4	4.19E+4	2.18E+5	2.05E+5	4.97E+5	4.21E+5	36

TABLE 11. *(continued)*

			For each building				For the un-renovated Vaasa stock				
			Current annual cost (€/year)	Proposed annual cost (€/year)	Current annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Proposed annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Current annual cost (€/year)	Proposed annual cost (€/year)	Current annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Proposed annual fuel life cycle GHG emissions (kg CO_2 equiv/year)	Option Priority
Wood	–1959	Det.	1.12E+3	1.11E+3	1.50E+4	1.41E+4	4.77E+5	4.74E+5	6.39E+6	6.01E+6	17
		Att.	3.51E+3	3.48E+3	4.70E+4	4.46E+4	6.34E+3	6.28E+3	8.48E+4	8.05E+4	50
		Mult	5.89E+3	5.81E+3	7.89E+4	7.40E+4	*				—
	1960–1969	Det.	1.15E+3	1.15E+3	1.55E+4	1.44E+4	1.43E+5	1.42E+5	1.92E+6	1.79E+6	30
		Att.	6.42E+3	6.35E+3	8.59E+4	8.07E+4	8.23E+3	8.15E+3	1.10E+5	1.04E+5	49
		Mult	1.47E+4	1.44E+4	1.96E+5	1.81E+5	*				51
	1970–1979	Det.	1.14E+3	1.14E+3	1.52E+4	1.52E+4	2.10E+5	2.10E+5	2.81E+6	2.81E+6	—
		Att.	4.56E+3	4.56E+3	6.11E+4	6.11E+4	1.89E+4	1.89E+4	2.52E+5	2.52E+5	51
		Mult	1.27E+4	1.26E+4	1.70E+5	1.59E+5	*				—
	1980–1989	Det.	1.12E+3	1.12E+3	1.49E+4	1.49E+4	2.45E+5	2.45E+5	3.28E+6	3.28E+6	51
		Att.	3.54E+3	3.53E+3	4.75E+4	4.49E+4	3.42E+4	3.40E+4	4.58E+5	4.33E+5	44
		Mult	1.10E+4	1.07E+4	1.47E+5	1.35E+5	*				—
	1990–1999	Det.	1.09E+3	1.09E+3	1.46E+4	1.46E+4	1.64E+5	1.64E+5	2.19E+6	2.19E+6	51
		Att.	3.04E+3	3.04E+3	4.08E+4	4.08E+4	9.54E+3	9.54E+3	1.28E+5	1.28E+5	51
		Mult	7.39E+3	7.39E+3	9.90E+4	9.90E+4	*				—
	2000+	Det.	8.46E+2	8.46E+2	1.13E+4	1.13E+4	1.22E+5	1.22E+5	1.63E+6	1.63E+6	51
		Att.	3.01E+3	3.01E+3	4.03E+4	4.03E+4	1.40E+4	1.40E+4	1.88E+5	1.88E+5	51
		Mult	7.86E+3	7.86E+3	1.05E+5	1.05E+5	*				—
Dist	–1959	Det.	1.73E+3	1.71E+3	7.41E+3	6.97E+3	7.40E+5	7.33E+5	3.17E+6	2.98E+6	27
		Att.	5.01E+3	4.97E+3	2.33E+4	2.21E+4	3.62E+4	3.59E+4	1.68E+5	1.60E+5	48
		Mult	7.95E+3	7.87E+3	3.91E+4	3.67E+4	2.11E+6	2.09E+6	1.04E+7	9.75E+6	11
	1960–1969	Det.	1.77E+3	1.76E+3	7.66E+3	7.15E+3	2.20E+5	2.18E+5	9.52E+5	8.89E+5	37
		Att.	9.88E+3	9.80E+3	4.26E+4	4.00E+4	5.07E+4	5.03E+4	2.18E+5	2.05E+5	47
		Mult	2.49E+4	2.46E+4	9.73E+4	8.95E+4	2.16E+6	2.13E+6	8.44E+6	7.76E+6	10
	1970–1979	Det.	1.75E+3	1.75E+3	7.54E+3	7.54E+3	3.24E+5	3.24E+5	1.39E+6	1.39E+6	51
		Att.	7.04E+3	7.04E+3	3.03E+4	2.72E+4	1.16E+5	1.16E+5	5.00E+5	4.50E+5	41
		Mult	2.19E+4	2.17E+4	8.44E+4	7.87E+4	2.64E+6	2.62E+6	1.02E+7	9.48E+6	8
	1980–1989	Det.	1.73E+3	1.73E+3	7.40E+3	6.48E+3	3.79E+5	3.79E+5	1.62E+6	1.42E+6	25
		Att.	5.86E+3	5.83E+3	2.35E+4	2.22E+4	2.26E+5	2.25E+5	9.07E+5	8.58E+5	42
		Mult	1.85E+4	1.82E+4	7.29E+4	6.71E+4	1.71E+6	1.68E+6	6.73E+6	6.20E+6	13
	1990–1999	Det.	1.70E+3	1.70E+3	7.22E+3	7.22E+3	2.56E+5	2.56E+5	1.09E+6	1.09E+6	51
		Att.	5.13E+3	5.13E+3	2.02E+4	2.02E+4	6.43E+4	6.43E+4	2.53E+5	2.53E+5	51
		Mult	1.28E+4	1.28E+4	4.91E+4	4.91E+4	1.29E+6	1.29E+6	4.96E+6	4.96E+6	51
	2000+	Det.	1.43E+3	1.43E+3	5.61E+3	5.61E+3	2.06E+5	2.06E+5	8.10E+5	8.10E+5	51
		Att.	5.22E+3	5.22E+3	2.00E+4	2.00E+4	9.72E+4	9.72E+4	3.72E+5	3.72E+5	51
		Mult	1.37E+4	1.37E+4	5.21E+4	5.21E+4	4.64E+5	4.64E+5	1.76E+6	1.76E+6	51

* It has been assumed there are no buildings in this category

TABLE 12. Number of Vaasa un-renovated residential buildings and apartments.

Construction decade[1]	Number of buildings			Number of apartments		
	Detached buildings	Attached buildings	Multistory buildings	Detached buildings	Attached buildings	Multistory buildings
–1959	2,110	36	492	2,208	145	3,816
1960–69	614	26	161	661	179	3,735
1970–79	959	87	235	964	413	4,628
1980–89	1,140	203	180	1,215	915	2,905
1990–99	782	66	197	840	269	2,274
2000–06	750	98	66	770	426	829
Total	6,355	516	1,331	6,658	2,347	18,187

[1]Buildings classified as "unknown" were omitted from our assessment.

TABLE 13. Baseline heat source by building class.

Building Class	Oil heat	Electric heat	Wood/ peat heat	District	Ground source heat
Detached	30%	29%	20%	20%	1%
Attached	22%	53%	5%	20%	0%
Multistory	30%	16%	0%	54%	0%

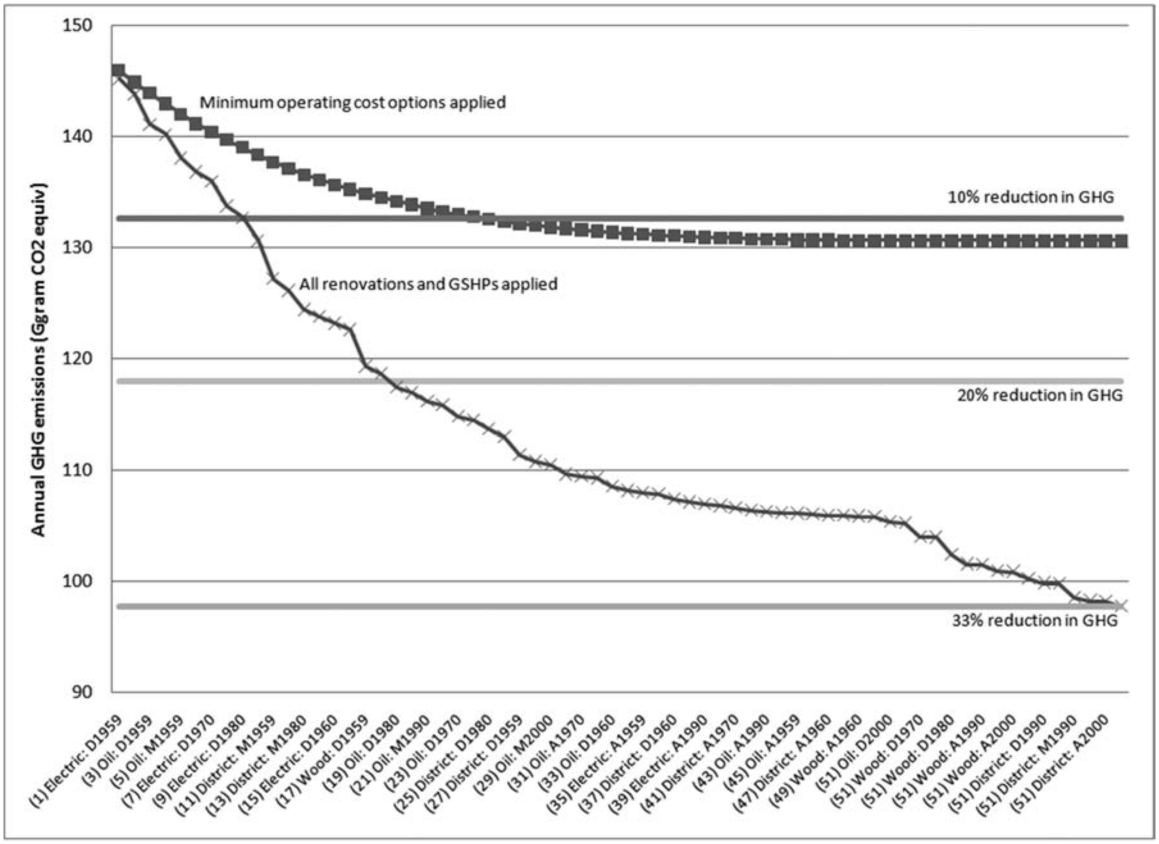
RETScreen model for the assessment of GSHPs proved extremely valuable. The combination of these data and models with LCA and cost data and methods allowed the development of an assessment tied to specific building types and ultimately to specific aspects of renovation and heating technology performance. In the process of combining these concepts and procedures, the importance of and a method for the segmenting the identification and assessment of the minimum-operating-cost scenarios by heat source were revealed.

Given these relatively available data and computational tools, we were able to prepare what we recognize are somewhat limited estimates of the life cycle cost and GHG implications. Specifically on the emissions side, although we were able to estimate the fuel life cycle GHG emissions of the fuels (from oil extraction, mining, or biomass growth to fuel use), data for equipment construction and maintenance and performance degradation as a function of equipment age remained elusive. We had a similar experience in our attempt to estimate life cycle costs: whereas the estimation of the cost of renovations, GSHP installations, and heat were performed using readily available data, the on-going costs of the maintenance of the renovated features, equipment maintenance, and the cost of equipment replacements were not readily found.

We anticipate some specific and general implications of our data limitations. Specifically, our estimate of potential reductions for the implementation of all the minimum operating cost options with GSHP installations represent an overestimation of the impact of GSHP applications as there is a lack of consideration of the number of sites where GSHPs would actually be applicable. Thus, although we are more confident in our estimation of potential savings on an individual building basis, our estimation of the potential savings for the Vaasa un-renovated stock are surely an overestimate.

Generally, there is a very wide range of performance indicators not considered in our study. On the cost side, capital equipment costs including the replacement of equipment for any of the heat

FIGURE 4. Estimation of the potential reductions in fuel life cycle GHG emissions for the un-renovated Vaasa stock.



sources over the 25-year study period, the cost of maintenance, and the cost of equipment decommissioning have not been included. Similar omissions have been made on the GHG emissions side. Further, there is a host of renovation options, distributed energy technologies, and sustainability/ performance metrics beyond those considered here. Examples are provided by Kaklauskas, et al. [33], who prioritize implementation strategies considering a large number of both indicators and renovation scenarios. In fact, they note that considering a wide variety of renovation technologies can bring the number of feasible alternatives to as large as 100,000. In order to consider not only this great number of supply and demand-side technology options and a wide variety of performance indicators, Kaklauskas, et al. describe decision-making models and methods (cost–benefit analysis, multiple criteria analysis, etc.), develop a multi-criteria prioritization method, and provide a case study that includes life cycle cost considerations. Although LCA based performance indicators are not included, the multi-criteria prioritization method provides a framework for such an addition. Further, the use of the length of the line from the current cost and GHG emissions point on a cost vs. emissions plot is reminiscent of the application of Data Envelopment Analysis (DEA), which can be used to prioritize options in multiple dimensions/ for multiple options and indicators as developed by Smith and Peirce [36].

Herein, the need to consider a more complete set of technologies on both the supply and demand sides (as listed in Table 1), the consequences of changes in the availability of heat as renovations are performed

TABLE 14. Variation prioritization as a function of the cost of heat (€/kWh).

<table>
<tr><th rowspan="2"></th><th rowspan="2">Baseline ranking</th><th colspan="2">Variation in the cost of oil</th><th colspan="2">Variation in the cost of electricity</th><th colspan="2">Variation in the cost of wood/peat heat</th><th colspan="2">Variation in the cost of district heat</th></tr>
<tr><th>–50%</th><th>+50%</th><th>–50%</th><th>+50%</th><th>–50%</th><th>+50%</th><th>–50%</th><th>+50%</th></tr>
<tr><td colspan="10">New rank</td></tr>
<tr><td>Electric: D1959</td><td>1</td><td>1</td><td>3</td><td>16</td><td>1</td><td rowspan="10">Same as the baseline</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Oil: M1970</td><td>2</td><td>11</td><td>4</td><td>1</td><td>2</td><td>3</td><td>2</td><td>3</td></tr>
<tr><td>Oil: D1959</td><td>3</td><td>41</td><td>2</td><td>2</td><td>4</td><td>4</td><td>3</td><td>6</td></tr>
<tr><td>Electric: M1959</td><td>4</td><td>2</td><td>5</td><td>14</td><td>3</td><td>5</td><td>4</td><td>7</td></tr>
<tr><td>Oil: M1959</td><td>5</td><td>14</td><td>1</td><td>3</td><td>5</td><td>6</td><td>5</td><td>8</td></tr>
<tr><td>Oil: M1960</td><td>6</td><td>12</td><td>7</td><td>4</td><td>6</td><td>7</td><td>6</td><td>9</td></tr>
<tr><td>Electric: D1970</td><td>7</td><td>3</td><td>9</td><td>18</td><td>8</td><td>8</td><td>7</td><td>10</td></tr>
<tr><td>District: M1970</td><td>8</td><td>4</td><td>11</td><td>5</td><td>9</td><td>9</td><td>51</td><td>2</td></tr>
<tr><td>Electric: D1980</td><td>9</td><td>5</td><td>12</td><td>15</td><td>7</td><td>10</td><td>8</td><td>11</td></tr>
<tr><td>District: M1960</td><td>10</td><td>6</td><td>13</td><td>6</td><td>10</td><td>11</td><td>51</td><td>12</td></tr>
<tr><td colspan="10">New to the top ten</td></tr>
<tr><td>District: M1959</td><td>11</td><td>7</td><td></td><td>7</td><td rowspan="8">none</td><td rowspan="8">none</td><td rowspan="8">none</td><td></td><td>4</td></tr>
<tr><td>Oil: M1980</td><td>12</td><td></td><td>10</td><td>8</td><td>9</td><td></td></tr>
<tr><td>District: M1980</td><td>13</td><td>8</td><td></td><td>9</td><td></td><td>5</td></tr>
<tr><td>Electric: M1970</td><td>14</td><td>9</td><td></td><td></td><td>10</td><td></td></tr>
<tr><td>Electric: D1960</td><td>15</td><td>10</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Wood: D1959</td><td>17</td><td></td><td></td><td>10</td><td></td><td></td></tr>
<tr><td>Oil: D1970</td><td>23</td><td></td><td>6</td><td></td><td></td><td></td></tr>
<tr><td>Oil: D1980</td><td>26</td><td></td><td>8</td><td></td><td></td><td></td></tr>
</table>

and distributed capacity is added, a broader definition of cost an GHG emissions, and a wider range of environmental, economic, and societal implications is critical. For example, for social implications LEnSE (see http://www.lensebuildings.com/) lists well-being, user comfort, and occupant's health among assessment criteria. To the economic implications understood through life cycle costing, LEnSE adds consideration of regional implications. Specifically, LEnSE suggests support for local economies and externalities such as health costs for the local community and reducing any detrimental effects on surrounding historical buildings are included in sustainable building assessments.

Finally, although evaluating ex post policy development, Harmelink, et al. [34] provides a characterization of the use of policy theory for energy efficiency policy evaluation that can be modified for policy development and thus provides insight here. Harmelink, et al., based on the works of Rufo et al. 1999 [35] and others, suggest an iterative, continuous improvement focused process to dissect a policy in a way that reveals explanatory factors behind any impact and facilitates policy improvement. The framework and case study presented here provide several points of integration with Harmelink, et al.'s six-step policy theory process as shown in Table 15. Specifically, we have presented methods for the identification of the target groups (including a classification of groups/building owners by building type, construction year, and current heat source), provided targets at both the building and regional levels, identified which actors needs to take action and the expected outcome of each action, developed the

TABLE 15. Mapping the framework and case study presented here to the policy theory process.

Steps in the application of policy theory	Aspects included in the framework and case study presented here	Remaining aspects
1. Characterization of the policy instrument	• Identification of the target groups – Owners of un-renovated buildings • A description of targets – For Vaasa, a 20% emissions reduction target for greenhouse gases by 2020 as suggested by the European Commission • Preparation of the available information on the initially expected energy savings impact and the cost effectiveness of the instrument – As presented in Section 3	• The identification of the policy-implementing agents and budget • The period the policy instrument was or is to be active
2. Develop policy theory	• Identification of which actor needs to take action – Building owners by building type, construction year, and current heat source • The expected outcome of each action – Reductions in operating costs – Reductions in the fuel life cycle GHG emissions	• Documenting implicit and explicit assumptions in the policy implementation process and mapping the cause–impact relationship, including the relationship with other policy instruments.
3. Policy theory translation	• The development of the necessary formulas to calculate the impact and cost effectiveness – As presented in Sections 3.1-3.2 • Translation of the policy theory into concrete and preferably quantitative indicators, based on – Again as in Sections 3.3-3.4	
4. Depiction of cause-impact relationships	• The cause–impact relations and the indicators are visually reflected in a flowchart. – Although not a flowchart, Figure 4 provides an alternative new of cause-impact	
5. Verification and adjustment of the policy theory		• Interviews with policy makers, implementing agents, and other actors involved in the implementation and monitoring of the policy instrument
6. Measure impact and formulate policy improvement options		• Available information is gathered and analyzed to draw up the indicators • Conclusions are drawn on the energy savings impact and cost effectiveness of the policy instrument using the formulas and indicators • Analyses are made on the success and failure factors attributed to the analyzed instruments • Recommendations are formulated to improve the energy savings impact and cost effectiveness

necessary formulas to calculate the impact and cost effectiveness, translation of the policy theory into concrete and preferably quantitative indicators (based on building and distributed energy performance models), and provided an alternative depiction of the cause–impact relations and the indicators (i.e., an alternative to flow-charting). Further, as input to policy development or evaluation using policy theory, we have suggested a wide range of technology options for energy efficiency in the building sector (Table 1).

5. CONCLUSIONS AND CONTINUING RESEARCH

It is possible to connect data and computational models of building and distributed energy performance with cost and GHG emissions data to identify improvement scenarios given regionally-specific conditions for renovations and GSHPs and more generally other building and distributed energy technologies. Whereas the expected performance of GSHPs can be estimated for any region using the RETScreen tool, access to tools for estimating regionally-code specific building heat demands are needed to apply the framework to other regions. Given such tools, application to other regions can proceed from: (1) the estimation of the demand for heat by building class that includes consideration of building codes during the year of construction (as in Section 3.1), (2) the estimation of GHG emissions and costs (as in Section 3.2), (3) the identification of the minimum-operating-cost options (as in Section 3.3), to (4) the evaluation of the minimum-operating-cost options (as in Section 3.4) for individual buildings and the region as a whole. Moving beyond the case study presented here requires not only knowledge of distributed generation site suitability but also data to extend the operating costs and fuel life cycle GHG emissions to include additional components of life cycle cost and LCA as well as additional technologies and sustainability performance metrics.

Finally, using the method presented herein, characteristics achievable in future work include:

- A broader scope for the estimation of costs and life cycle GHG emissions;
- Use of a wider range of sustainability indicators (environmental, economic, and social);
- Selection of a wider range of demand and supply side technologies;
- The addition of LCAs for the renovation materials and heat technology production and maintenance; and
- Consideration of a larger set of possible management schemes (e.g., based on the current heat source, based on neighbourhood characteristics).

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