Life Cycle Assessment
Of a
Deep Energy Retrofit

Prepared for ENVR E-150: Life Cycle and Risk Assessment
Harvard University Extension School
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Image on the cover: The home in this case study after the completion of the Deep Energy Retrofit project.

Abstract

Some of the country's oldest housing stock is located in its colder regions. Older housing is typically less energy efficient. Aging homes that require replacement of siding, roofs, HVAC equipment, windows, and appliances present opportunities to improve energy efficiency. A Deep Energy Retrofit (DER) is an extensive, multi-system type of home renovation project that seeks to reduce the home's energy consumption by 50-95%. Yet in order to achieve such energy efficiency, newly manufactured materials are installed while much of the existing structure is removed and disposed of. Energy savings and CO_2 emission reduction metrics for these projects are impressive. Yet the existing literature does not address questions of the overall net environmental impact of a DER. What are the environmental impacts of the materials and processes that are required to reduce the carbon footprint? This lifecycle assessment (LCA) examines the environmental costs and benefits of a DER that is expected to achieve an 85% reduction in home heating energy usage. By assembling the unit processes and creating a life cycle inventory, we can see the impact or environmental costs of the major inputs — new insulation, new boiler, new windows, construction work, and the waste scenario — against the benefits using less energy from a cleaner fuel. The findings indicate that a DER as exemplified by this case study is an environmentally beneficial project when greenhouse gas reduction and global warming are the priority targets. Life cycle assessment can also be used to focus public and commercial attention on reducing the environmental costs of the unit processes that make such energy and greenhouse gas (GHG) reductions possible.

Introduction

What is the net environmental impact of a deep energy retrofit? We know that adding insulation, a more efficient furnace, modern windows and leak sealing foam to an older house will reduce the energy required to maintain a given temperature. We can calculate the cost savings and GHG reductions. But what of the environmental impacts from all of the inputs to such a project? To what extent do the upstream and downstream processes in the technosphere effect nature, and how much of our environmental improvement from burning less fossil fuel is offset by the manufacture and transport of the products needed to achieve that reduction? This life cycle assessment (LCA) seeks to address these questions.

Massachusetts possesses some of the oldest housing stock in the nation, with close to 68% of housing units built prior to 1970, 44% built prior to 1950, and 39% built before 1940, and according to the U.S. Bureau of the Census, Census 2000. Many homes, especially in the Northeast, rely on home heating oil to fuel their furnaces. And older homes are often poorly insulated and leaky. This region presents many, many opportunities to save energy and greenhouse gas emissions with more efficient housing.

The house owned by me and my wife is a Dutch Colonial built in 1930, and it is typical of the great majority of homes in the Northeast. The walls have no original insulation, and any attic and basement / foundation protection from the outside cold was added, without professional assistance, in the 1970s and 80s. It is cold and drafty for half of every year. We spend too much to heat the house to 56 to 62 degrees. We would like to improve our environmental citizenship by burning less fuel.

I began to learn about home energy retrofitting in ENVR E-102; we saw class videos of Professor Bill Moomaw's zero net energy house in western Massachusetts. I engaged our utility company for a home energy audit, complete with infrared photographs, which confirmed the lack of insulation in the walls and highlighted other energy saving opportunities throughout the house. We made the do-it-yourself improvements. The house is still cold and costly, and we genuinely desire to consume less from the planet, especially in terms of fossil fuels and GHG impact. When I learned of a pilot program for deep energy retrofitting offered via our gas utility, National Grid, I contacted the company to learn if our house is a candidate for the program. Those discussions are ongoing. In researching material for this project proposal, I learned of a completed DER a few blocks away. We attended the open house at that property, hosted by the owners, in conjunction with National Grid and Byggmeister, Inc, the design firm, showcasing the Deep Energy Retrofit of the home. When the owner offered to share the data from their project, the lure was irresistible. This LCA project therefore uses data from the Brownsberger DER project as proxy for our house in Belmont. The houses are approximately the same size, subject to the same weather and economic conditions.

A DER is a home rebuilding project for super-insulating older homes and making mechanical upgrades in order to reduce the amount of energy required for heating (and often cooling, lighting and appliances as well) by 50% to 95%. Other characteristics of a DER include air sealing, moisture management, ventilation control, and heat exchange to achieve energy savings and improved building performance. Flashing and air sealing of windows and other building openings are also key to a successful DER. Systems thinking is required for these kinds of retrofits, where highly efficient windows are "tuned" to their orientation, and mechanical systems and heat recovery ventilation units are sized and integrated with how the walls, roof and basement are being air sealed, moisture-managed and insulated. A DER is generally more financially attractive when major renovations to the building are needed, such as re-siding, a new roof, and boiler replacement.

This Deep Energy Retrofit project in Belmont was completed in September of 2010 by Byggmeister, a design renovation firm from Newton, and is part of a comprehensive, whole house renovation of this 85-year old two family home. The DER was supported with financial and technical resources from National Grid, Building Science Corporation and Building America.

Highlights of the Belmont Deep Energy Retrofit

- Attic: R-60 (7’ Cellulose, 6” rigid polyisocyanurate foam added to exterior)
- Walls: R-40 (4” rigid polyiso foam added to exterior)
- Windows: R-5 0.2 U Pardigm triple glazed, low E, argon filled
- Air leakage reduction: > 85%, CFM 50 initial 5700, final less than 700
- Heating system: 95% efficient American Standard forced-air
- Heat recovery ventilation: Renewaire EV 130 (ERV)
- Lighting: Compact fluorescent or better throughout
- Appliances: ENERGY STAR®
- Renewables: Solar hot water with electric back-up

Beneficience

The analysis conducted for a DER project typically includes a financial estimate of the work to be performed, a construction plan, and model calculations for energy savings and CO_2 emission reductions. We do not know of any life cycle assessment that has been done in connection with one of these projects. The owners, the builder and National Grid have all expressed strong interest in incorporating LCA into the growing body of knowledge in this nascent field. In addition to these stakeholders, the project is included in the Thousand Home Challenge, a program to educate and promote home energy efficiency advances that can lead to energy reductions of 70-90% (1000 Home Challenge, p. 1). So opportunity to gain a multiplier — to showcase LCA analysis to many more stakeholders, beyond just one house project — and convince more owners to consider this kind of environmental investment, addresses the concept of positive handprint and beneficience. The author hopes this LCA contributes to “changing the path of reality with creativity and actions,” and helps to clean up another “acre.” Whether or not my wife and I decide to invest in a DER for our house, I can offer my handprint contribution to the field via this LCA project.

We know that a DER will reduce the energy load of a house, and we know that housing is one of the top three sectors (in addition to food and transportation) that are the biggest share of our footprint (Tucker, et al, p. 159). Yet what of the environmental impacts that come about as the result of the DER? A lot of material is removed to waste streams from the original structure, and new materials are installed. Transportation from factory to distribution to the site (and from site to disposal) is significant, and many ancillary activities contribute to environmental damage. What is the net impact? This LCA will attempt to address this question and illuminate other questions that arise from this assessment.

Goal & Scope

The goal of this assessment is to inventory and quantify the environmental impacts associated with the net energy reduction along with the building materials and other products and activities that comprise a deep energy retrofit for a typical example of aged housing in the Boston area. The study is conducted by the author, as part of the ENVR E-150 - Lifecycle and Risk Assessment, the course led by Professors Norris and Hayes at the Harvard Extension School's Sustainability & Environmental Management. The study is intended to be a cradle to grave analysis, and it is conducted with the assistance and interest of the owner of the Belmont DER site, Will Brownsberger, and the builder Paul Eldrenkamp of Byggmeister, Inc., a remodeling and design firm. The DER project-sponsoring energy company, National Grid has also expressed interest in the study (per David Legg). The study will be made available to multiple stakeholders.

The scope of the study is, initially, and for class submission by December 20th, 2010, limited to the home heating system, insulation and replacement windows. Electric power and hot water heating efficiency are not part of the initial phase of the project but may be included in subsequent phases.

The functional unit is defined as heating for a 4,100sq ft. 1925 2-family home required to maintain 58-65 degrees (depending on time of day).

- Allocation is based on a useful life of the structure of 85 years and 30 years for the HVAC equipment
- Data used reflect actual DER project values except where noted; energy use pre- and post DER completion is based on modeled projections.
- The boundaries of the system are the four walls, foundation and roof of the dwelling.
- Peer review will include the owner and builder and possibly additional stakeholders.
- The intended audience is ENVR E-150 class instructors and students, the DER owner and builder, and other DER-interested parties who express interest.

Lifecycle Inventory

The system described in this assessment is based primarily on actual materials and processes in the completed Belmont DER. Data was gathered via a series of interviews with the builder and owner, as well as literature search. Proxies are used for the new high efficiency windows and for polyisocyanurate insulation panels, as described below.

In this DER project, oil heat is eliminated in favor of a natural gas heating system. Assumptions for the amount of home heating oil #2 that will be displaced by the new natural gas heating system and the amount of natural gas that will be required to heat the retrofit dwelling are based on output from the Home Energy Rating System (HERS) model and the REMRate software program (Eldrenkamp, p. 1). Conversion calculations were made to translate between MJ, Btu, therms and gallons where appropriate (see Appendix A).

The useful life of the structure is assumed to be 85 years, so building materials are divided by 85 to arrive at annual usage amounts. HVAC equipment is assumed to last for 30 years. The previous structure, including the aged heating unit, served for 85 years.

The unit processes and the respective quantities of each that have been included in the LCI include:

Table 1: Lifecycle Inventory

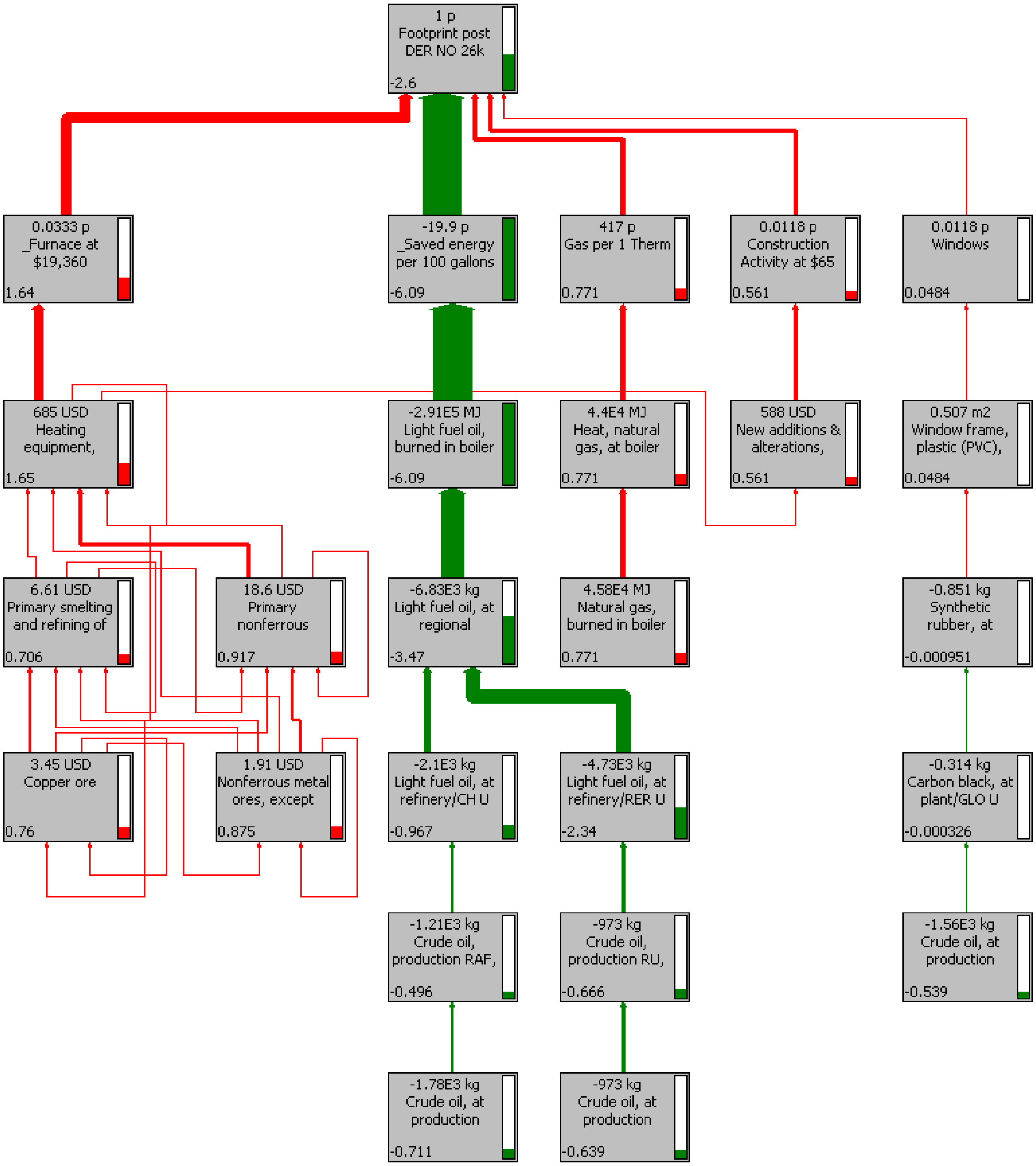
Reference Flows	Units	Notes & Assumptions
Baseline: 26 x One 2002 Dollar US Consumer Spending Impacts	US dollar	Project assignment data
Heating equipment, except electric and warm air furnaces	$19,360	Assume 30 year life US Input Output Database
Window frame, plastic (PVC), U=1.6 W/m2K, at plant/RER U Proxy for: *58 Windows (3x pane, argon/krypton filled)*	464 sq ft	Assume 85 year life Ecoinvent unit process
Cellulose fibre, inclusive blowing in, at plant/CH U	8,600 lbs	Assume 85 year life Ecoinvent unit process
Polystyrene foam slab, 45% recycled, at plant/CH U Proxy for: *Polyisocyanurate panels*	2,700 lbs	Assume 85 year life Ecoinvent unit process
Polyurethane rigid foam E	450 lbs	Assume 85 year life Ecoinvent unit process
Rock wool, packed, at plant/CH U	700 lbs	Assume 85 year life Ecoinvent unit process
New additions & alterations, nonfarm, construction	$50,000	766 hours @ $65 / hour US Input Output Database
Heat, natural gas, at boiler modulating <100kW/RER U	417 Therms; 105.506 MJ per Therm.	The amount of heat energy forecast by HERS model Ecoinvent unit process
Light fuel oil, burned in boiler 10kW, non-modulating/CH U	1,990 gallons; 13,870,000 Btu per 100 gallons	The amount of home heating oil eliminated Ecoinvent unit process
Waste Scenario:		
Disposal, building, window frame, wood, to final disposal/CH U	464 sq ft	Estimate Ecoinvent unit process
Disposal, building, waste wood, untreated, to final disposal/CH U	2,200 lbs	Estimate Ecoinvent unit process
Disposal, building, plaster board, gypsum plaster, to final disposal/CH U	2,200 lbs	Estimate Ecoinvent unit process
Disposal, building, glass sheet, to final disposal/CH U	330 lbs	Estimate Ecoinvent unit process

Inventory Analysis Method

IMPACT 2002+ version was chosen for this assessment because it was developed relatively recently, and it is expected to be robust as it is a combination of IMPACT 2002, Eco-indicator 99, CML 2000 and IPCC. Further, it includes characterization, damage assessment, normalization and evaluation (Eco-indicator and ReCipe only include the first two). Finally, in this method damage assessment is depicted in 4 categories — human health, ecosystem quality, climate change and resources. Other methods include only three aggregated impact groupings (human health and climate change are combined).

The resulting network process tree with the relevant processes is shown in part here:

Figure 1: Network Diagram - Deep Energy Retrofit Unit Processes (8.7% resolution)



Results: Lifecycle Impact Assessment

The most immediate finding from this assessment is an improvement in every impact category, as shown in Table 2, stemming from the anticipated 85% reduction in energy required to heat the dwelling, Here we compare the amount of fuel oil required to heat the dwelling pre-DER, and the anticipated amount of natural gas after replacing the heating system and completing the retrofit.

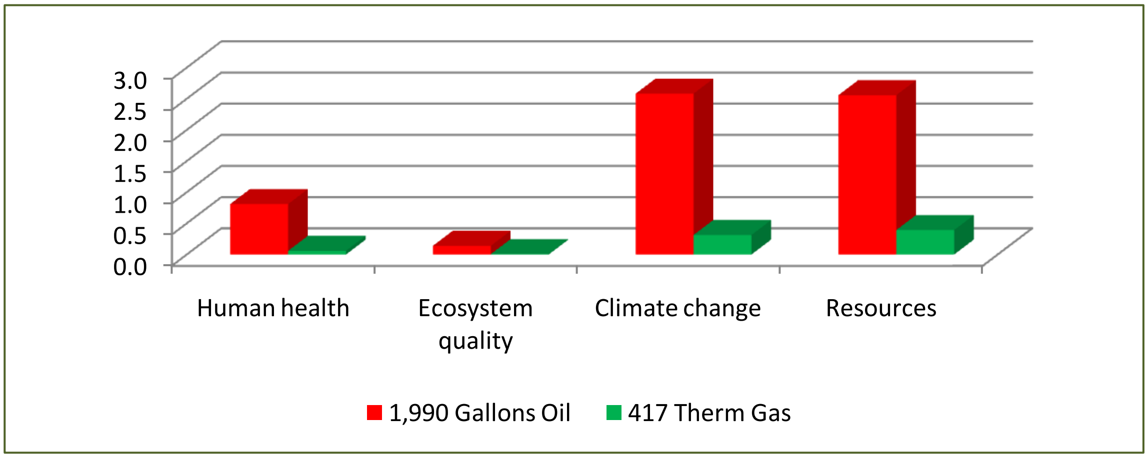
Table 2: Old vs. New Heating Fuels and Amounts Compared

Impact category	Unit	OLD: 1,990 Gallons Fuel Oil	NEW: 417 Therm Gas	Change	% Change
Carcinogens	kg C2H3Cl eq	76.2	34.5	**(42)**	-55%
Non-carcinogens	kg C2H3Cl eq	67.6	3.7	**(64)**	-95%
Respiratory inorganics	kg PM2.5 eq	7.6	0.4	**(7)**	-94%
Ionizing radiation	Bq C-14 eq	140,096	7,591	**(132,504)**	-95%
Ozone layer depletion	kg CFC-11 eq	0.0038	0.0005	**(0)**	-86%
Respiratory organics	kg C2H4 eq	8.4642	0.7567	**(8)**	-91%
Aquatic ecotoxicity	kg TEG water	885,005	33,550	**(851,455)**	-96%
Terrestrial ecotoxicity	kg TEG soil	209,632	8,975	**(200,657)**	-96%
Terrestrial acid/nutri	kg SO2 eq	171.4	12.4	**(159)**	-93%
Land occupation	m2org.arable	29.7	1.0	**(29)**	-97%
Aquatic acidification	kg SO2 eq	54.5	3.1	**(51)**	-94%
Aquatic eutrophication	kg PO4 P-lim	2.3	0.1	**(2)**	-97%
Global warming	kg CO$_2$ eq	25,560	3,101	**(22,459)**	-88%
Non-renewable energy	MJ primary	388,436	59,621	**(328,815)**	-85%
Mineral extraction	MJ surplus	112.0	7.5	**(104)**	-93%

Source: SimaPro; Heat, natural gas, at boiler modulating <100kW/RER U vs. Light fuel oil, burned in boiler 10kW, non-modulating/CH U

The normalized view of this series of impact category improvements, depicted in aggregated format, is shown in Figure 2 below, in which we can see the relative magnitude of the fuel-driven benefits accruing to Human health, Ecosystem quality, Climate change and Resources

Figure 2: Old vs. New Heating Fuels / Amounts Compared



Substituting 417 therms of natural gas for 1,990 gallons of home heating oil is equivalent to reducing 276.6 million Btu to 41.7 Btu (85%), which results in 38,850 lbs of CO$_2$ saved from emission. A simple calculation of the annual benefit in CO$_2$ emissions shows a nearly 40,000 lb. benefit:

Table 3: CO$_2$ Emissions Saved from Gas to Oil Switch

Metric	Gas	Oil	Change
Therm / Gallon	417	1,990	
Lbs CO$_2$ per unit	13.446	22.34	
LBS	5,606	44,457	(38,850)

If the scope of this analysis was limited to the fuel switch and savings alone, these improvements alone would be laudable.

Yet the purpose of conducting the LCA is to produce a holistic analysis of the environmental impacts by including all of the unit processes that contribute to the increased fuel efficiency, and to understand the cost of these ancillary negative environmental impacts. Table 4 shows the characterization of all of the unit processes that make up the DER, including the HVAC equipment, the 12,450 pounds of insulation, construction activity, newly manufactured and installed windows, and the waste stream (the plaster, wood, glass, etc. removed from the old structure) — in addition to the fuel type and quantity switch shown above. The sum of these impacts is shown as *Total Change to Footprint* (third column from left).

Now we see that the environmental sums per category are not all positive. The DER project is damage-additive for carcinogens, non-carcinogens, aquatic and terrestrial toxicity and land occupation. The project is still net positive for, most notably, global warming and non-renewable energy.

Table 4: Impact Category Summary

Impact category	Unit	Total Change to Footprint	Furnace	Insulation	1,990 Gallons Fuel Oil	Gas 417 Therm	Construction	Windows	Waste Stream
Carcinogens	kg C2H3Cl eq	**300**	226	2	(76.2)	35	52	3	59
Non-carcinogens	kg C2H3Cl eq	**3,061**	2,315	0	(67.6)	4	505	4	301
Respiratory inorganics	kg PM2.5 eq	**-3.02**	0.69	0.05	(7.6)	0.44	1.25	0.11	1.99
Ionizing radiation	Bq C-14 eq	**-127,667**	0	1,114	(140,095.5)	7,591	0	2,009	1,714
Ozone layer depletion	kg CFC-11 eq	**0.000060**	0.001207	0.000004	(0.0)	0.000517	0.002102	0.000005	0.000017
Respiratory organics	kg C2H4 eq	**-5.74**	0.66	0.08	(8.5)	0.76	0.87	0.12	0.24
Aquatic ecotoxicity	kg TEG water	**1,636,131**	1,977,616	2,140	(885,004.7)	33,550	480,742	9,956	17,132
Terrestrial ecotoxicity	kg TEG soil	**772,704**	777,880	529	(209,632.2)	8,975	186,979	5,230	2,743
Terrestrial acid/nutri	kg SO2 eq	**-99**	10	1	(171.4)	12	13	4	33
Land occupation	m2org.arable	**44**	22	2	(29.7)	1	44	2	2
Aquatic acidification	kg SO2 eq	**-10**	3	0	(54.5)	3	3	1	35

Aquatic eutrophication	kg PO4 P-lim	**-2**	0	0	(2.3)	0	0	0	0
Global warming	kg CO2 eq	**-20,247**	605	61	(25,560.2)	3,101	568	120	859
Non-renewable energy	MJ primary	**-307,653**	7,845	1,592	(388,435.9)	59,621	6,902	2,892	1,932
Mineral extraction	MJ surplus	**-82**	3	1	(112.0)	7	1	15	2

Source: SimaPro

In order to begin to gauge the magnitude and the significance of these positive and negative environmental impacts, we look at the Changes to Footprint for each impact category next to the baseline footprint calculated from $26,000 annual consumer spending. The overall change in the footprint from all of the unit processes can be seen in the Table 5 below.

By looking at the Change % figures (column at far right), we see that the improvements in climate change and non-renewable energy (lines13 and 14) appear to be very significant relative to the same metrics inherent in $26,000 of consumer spending. The DER project also has solid positive impacts on respiratory organics and terrestrial acidification (lines 6 and 9), largely due to the switch in fuel type.

Table 5: Total Changes to Footprint

Line Ref	Impact category	Unit	$26k Footprint	Total Change to Footprint	Change %
1	Carcinogens	kg C2H3Cl eq	4,342	**300**	7%
2	Non-carcinogens	kg C2H3Cl eq	43,718	**3,061**	7%
3	Respiratory inorganics	kg PM2.5 eq	51.48	**-3.02**	-6%
4	Ionizing radiation	Bq C-14 eq	0	**-127,667**	
5	Ozone layer depletion	kg CFC-11 eq	0.000000	0.000060	
6	Respiratory organics	kg C2H4 eq	15.31	**-5.74**	-38%
7	Aquatic ecotoxicity	kg TEG water	95,464,954	**1,636,131**	2%
8	Terrestrial ecotoxicity	kg TEG soil	473,456,533	**772,704**	0%
9	Terrestrial acid/nutri	kg SO2 eq	390	**-99**	-25%
10	Land occupation	m2org.arable	21,060	44	0%
11	Aquatic acidification	kg SO2 eq	390	**-10**	-3%
12	Aquatic eutrophication	kg PO4 P-lim	0	**-2**	
13	Global warming	kg CO2 eq	19,500	**-20,247**	-104%
14	Non-renewable energy	MJ primary	242,320	**-307,653**	-127%
15	Mineral extraction	MJ surplus	0	**-82**	

Source: SimaPro

These outputs from the DER project cause midpoint effects (e.g., heat trapping in the atmosphere). These midpoints then lead to consequences or “endpoints” (e.g., flooding of low lying areas, increases in malaria, etc.). These endpoints can be aggregated into “damage categories.” The four primary damage categories are Human Health, Ecosystem Quality, Resource Depletion and Climate Change. These damage categories are expressed in equivalents in order to make comparisons more tangible. Human health is expressed in DALYs, Disability Adjusted Life Years. This accounts for mortality and morbidity factors. Ecosystem quality is expressed in PDF*m^2*yr, the Potentially Displaced Fraction of Species over a standard area (1 m^2) in one year. Resource depletion is expressed as MJ primary as the energy required to obtain these resources increases as the supply is reduced. Finally, climate change or global warming potential is expressed as a CO$_2$ equivalent (kg CO$_2$ eq).

Table 6 shows the endpoint summary in terms of the impact categories.

Table 6: Endpoint Summary by Impact Category

Impact category	Unit	Total Change to Footprint	Furnace	Insulation	1,990 Gallons Fuel Oil	Gas 417 Therm	Construction	Windows	Waste Stream
Carcinogens	DALY	0.001	0.0006	0.0000	-0.0002	0.0001	0.0001	0.0000	0.0002
Non-carcinogens	DALY	0.009	0.0065	0.0000	-0.0002	0.0000	0.0014	0.0000	0.0008
Respiratory inorganics	DALY	-0.002	0.0005	0.0000	-0.0053	0.0003	0.0009	0.0001	0.0014
Ionizing radiation	DALY	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ozone layer depletion	DALY	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Respiratory organics	DALY	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Aquatic ecotoxicity	PDF*m2*yr	82.13	99.27	0.107	-44.42	1.68	24.13	0.49	0.86
Terrestrial ecotox	PDF*m2*yr	6,112	6,153	4.18	-1,658	70.99	1,479	41.4	21.7
Terrestrial acid/nutri	PDF*m2*yr	-102	10.445	1.016	-178.25	12.87	13.24	3.79	34.41
Land occupation	PDF*m2*yr	47.5	24.39	2.66	-32.32	1.04	47.61	1.77	2.39
Aquatic acidification		-	-	-	-	-	-	-	-
Aquatic eutroph.		-	-	-	-	-	-	-	-
Global warming	kg CO2 eq	-20,246	604	61	-25,560	3,101	567	119	858
Non-renewable energy	MJ primary	-307,658	7,845	1,591	-388,448	59,620	6,901	2,891	1,931
Mineral extraction	MJ primary	-82.26	3.15	0.56	-111.96	7.50	0.82	15.23	2.45

Source: SimaPro

Table 7 shows the endpoint summary in terms of the four damage categories.

Table 7: Endpoint Summary by Damage Category

Damage Category	Unit	Total Change to Footprint	Furnace	Insulation	1,990 Gallons Fuel Oil	Gas 417 Therm	Construction	Windows	Waste Stream
Human health	DALY	0.0073	0.0076	0.0000	-0.0057	0.0004	0.0024	0.0001	0.0024
Ecosystem quality	PDF*m2*yr	6,139	6,287	8	-1,913	87	1,564	47	59
Climate change	kg CO2 eq	-20,247	605	61	-25,560	3,101	568	120	859
Resources	MJ primary	-307,735	7,848	1,592	-388,548	59,628	6,903	2,907	1,934

Source: SimaPro

Analysis & Interpretation

These results are roughly what we expected, at least directionally. There are environmental costs to consider with such an extensive project, beyond simple calculations for CO_2 and fossil fuel savings. Major structural, material investment is required in order to improve the energy demand of the dwelling by 85%.

Greenhouse gas reduction is one of the top priorities for projects of this kind, and this DER example achieves the goal of GHG reductions, even net of the GHG emitted from the additive unit processes - construction and the addition of newly manufactured materials. On Table 5, line 13 we see the calculated value of over 20,000 kg of CO_2 equivalents.[1] Drilling down into the SimaPro data, we see that the GHGs from the project unit processes include, not surprisingly, SOx, NOx, methane, and HFCs. Yet the reduction in the amount of fossil fuel consumed, as well as the switch from oil to gas, contributes the intended benefit of making the house a much lower emitter of GHGs.

One of the surprises was that the insulation used to super-insulate the home contributed the least to the environmental impacts despite having the greatest mass. This is probably because these products are largely constructed from recycled materials. Cellulose insulation is made from waste paper. Polystyrene foam slab (proxy for polyisocyanurate) is made from 45% recycled material. Nevertheless, the inventory for these materials includes energy used in their production and transportation. Further investigation is warranted of this category to assure the European-based Ecoinvent inventory data are reasonably comparable to North American materials and to understand discrepancies between proxy and actual insulation products.

Looking at lines 1 and 2 on Table 5, we might conclude that adding 7% to both carcinogens and non-carcinogens might not be significant. Yet much of this addition is due to the new HVAC equipment, as seen in Table 4, lines 1 and 2. Recall that the allocation of this equipment spreads the impact over 30 years, the useful life of the boiler, and thus the immediate impact of the manufacture and transportation of this asset is understated, when in fact all of this environmental damage occurs in the short term.

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[1] Greenhouse gases are those which allow ultraviolet energy from the sun to penetrate earth's atmosphere but trap infrared (IR) energy in the atmosphere, thereby causing an increase in the earth's temperature. The global warming potential of greenhouse gases such as SF_6, N_2O, H_2O_L and CFCs are benchmarked against a standard for CO_2 (units: kg CO_2 eq/kg). When considering global warming potential, we examine the ability of the gas to absorb IR energy over time (BTU/kg/min or MJ/kg/min). A GHG which absorbs a lower amount of energy but remains in the environment for a long time may, in fact, pose a larger long-term risk than one that absorbs a lot of energy initially but dissipates quickly. We should concern ourselves with long term GWP (100-500 years) when considering the fate of future generations. However, we should not disregard shorter term global warming potential (20 year figures) as short term disruptions could cause severe instability in the ecosystem and engage tipping points which may not be able to be reversed (e.g., melting of glaciers reducing the mirror effect on UV energy).

A sensitivity analysis is called for to respond to questions of a gas-to-gas comparison, for cases in which the DER does not call for a switch from oil to gas heat. When gas heat is already used to heat the building, we assume that the same amount of energy will be conserved. We therefore convert the 1,990 gallons of home heating oil to the equivalent number of Btus of natural gas. Table 8 shows that while since oil is a dirtier fuel, merely reducing the amount of gas already used in the home will not bring the same magnitude of benefits for most impact categories than for those scenarios which replace the oil heat.

Table 8: Oil vs. Gas Comparison - Same Energy Content

Impact category	Unit	1,990 Gallons Fuel Oil	2,766 Therm Gas	Comments
Carcinogens	kg C2H3Cl eq	76.25	228.87	Gas equivalent produces more carcinogens
Non-carcinogens	kg C2H3Cl eq	67.65	23.82	Gas emits 1/3 as much non-carcinogens as oil
Respiratory inorganics	kg PM2.5 eq	7.55	2.92	
Ionizing radiation	Bq C-14 eq	140,095	18,792	
Ozone layer depletion	kg CFC-11 eq	0.00379	0.00343	Par for ozone depletion
Respiratory organics	kg C2H4 eq	8.46	5.02	
Aquatic ecotoxicity	kg TEG water	885,004	218,772	1/4 aquatic ecotoxicity vs. oil
Terrestrial ecotoxicity	kg TEG soil	209,632	58,464	1/4 terrestrial ecotoxicity vs. oil
Terrestrial acid/nutri	kg SO2 eq	171.40	82.15	1/2 terrestrial acidity vs. oil
Land occupation	m2org.arable	29.65	6.32	Lower land disturbance
Aquatic acidification	kg SO2 eq	54.50	20.28	
Aquatic eutrophication	kg PO4 P-lim	2.29	0.38	1/6 less aquatic eutrophication
Global warming	kg CO2 eq	25,560	20,570	Almost par for global warming
Non-renewable energy	MJ primary	388,435	395,470	Ditto for non-renewable energy
Mineral extraction	MJ surplus	111.96	49.75	

Source: SimaPro

Transportation is probably understated in this LCA. Although transportation is included as part of several unit processes, the assessment did not include shipping from factory to distribution to job site as part of the scope of the LCA. Most of the data is based on actual project inputs and amounts, and including transportation would have diluted the accuracy of the assessment with highly uncertain assumptions. This is an area for further development of this LCA.

Waste is another area where further work to bring more rigor to the analysis. The material removed from the house is primarily wood, glass, and plaster. SimaPro data for these materials is based on 1990s Swiss practices for construction waste disposal, namely incineration. Further, the amounts and types of waste have not yet been verified with the builder. Note that unit process for heating equipment, new windows, and insulation includes waste / disposal calculations. The waste stream is very likely overestimated; better estimates of the mass of material removed will be included in the next iteration.

We must also note that much of the data upon which this LCA rests is applicable to conditions in Europe, where the research was conducted, and so it will be accurate for U.S. interests in varying degrees, depending on the variation in the composition of the unit processes.

Peer review is another iterative refinement practice that the author will pursue to further develop this LCA. A meeting with the builder and the owner is scheduled to present these results, incorporate modifications and address additional suggestions.

Next steps for this LCA are to include the electricity demand change from the old structure to the new DER home. This will look at the increases in efficiency versus the LCA implications of new LED and CFL lighting and EnergyStar appliances.

Beneficience

The LCA allows us to set up accounting about beneficience in a way that addresses each category of impact separately on its own terms. And we can see the tradeoffs we are making between them. In this project, we are trading GHG emission improvement for increases in certain toxicities. If we consider just global warming metrics, then this project fulfills the assigned objective of creating a handprint that compensates for our GHG-only footprint. The DER project reduces global warming by 20,247 kg of CO_2 equivalents, against the footprint amount of 19,500 kg CO_2 equivalents.

This DER project by itself does not, however, compensate for the rest of our (my) footprint. For a rough estimate of the overall footprint vs. handprint score, we can look at the weighting and single score for the project. Using impact method IMPACT 2002+, the DER project contributes a net total of 2.6 points toward offsetting a total score of 303 points for the standard $26,000 consumer spend. Clearly one would have a lot more work to do in terms of changing behavior, retrofitting infrastructure and related analyses in order to continue to increase one's handprint to compensate for the footprint.

This scoring and the previous analysis steps point to questions about the size and composition of **terrestrial ecotoxicity (line 9)**. This is another subsequent phase for this LCA.

Table 9 : DER Impact Category Weighting

Line Ref.	Impact category	Unit	Footprint: $26,000 Spend	DER Project Contribution
1	**Total**	Pt	**303.067**	**-2.598**
2	Carcinogens	Pt	1.714	0.118
3	Non-carcinogens	Pt	17.260	**1.209**
4	Respiratory inorganics	Pt	5.081	-0.298
5	Ionizing radiation	Pt	0.000	-0.004
6	Ozone layer depletion	Pt	0.000	0.000
7	Respiratory organics	Pt	0.005	-0.002
8	Aquatic ecotoxicity	Pt	0.350	0.006
9	Terrestrial ecotoxicity	Pt	273.388	**0.446**
10	Terrestrial acid/nutri	Pt	0.030	-0.007
11	Land occupation	Pt	1.676	0.003
12	Aquatic acidification	Pt	-	-
13	Aquatic eutrophication	Pt	-	-
14	Global warming	Pt	1.970	**-2.045**
15	Non-renewable energy	Pt	1.594	**-2.024**
15	Mineral extraction	Pt	0.000	-0.001

Source: SimaPro

Conclusion

The results of this LCA show that a DER project can make a positive contribution to GHG emissions, at the cost of adding toxic materials to nature. This has public policy and sustainable industry implications. I believe this LCA shows the merit of supporting and encouraging more such projects. We can make a strong argument that communities and society should focus first on GHG problem because it is the most immediate threat to the climate, biodiversity, agriculture and indeed the carrying capacity of the planet. Next, sustainable industrial practices and technological innovation can address the next-level challenges, namely the toxicities of the material processes, transportation, and waste streams that are inherent in these projects.

Working with various local stakeholders in the field of Deep Energy Retrofitting, the author of this LCA would like to contribute to the body of knowledge of Deep Energy Retrofitting so that this study may support good decisions around the extent and scope for DER projects as well as smaller insulation or energy-reduction projects.

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Appendix A: Supporting Calculations

Cellulose insulation - WALLS

Ref.	Metric	Calculation	Value	
	Square feet		3,262	
	Thickness	inches	3.5	
	Cubic feet		951	
	Weight per cubic foot	lbs / cubic foot	3.75	
	Cellulose insulation - WALLS	by weight	3,568	
	Assumption/Note			

Polyiso or proxy material - WALLS

Ref.	Metric	Calculation	Value	
	Square feet		3,262	
	Thickness	inches	4.0	
	Cubic feet		1,087	
	Weight per cubic foot	lbs / cubic foot	1.75	
	Polyiso or proxy material - WALLS	by weight	1,903	
	Assumption/Note	Proxy:		

Polyiso or proxy material - ROOF

Ref.	Metric	Calculation	Value	
	Square feet		1,708	
	Thickness	inches	6.0	
	Cubic feet		854	
	Weight per cubic foot	lbs / cubic foot	1.75	
	Polyiso or proxy material - ROOF	by weight	1,495	
	Assumption/Note			

Cellulose insulation - RAFTER CAVITIES

Ref.	Metric	Calculation	Value	
	Square feet		3,262	
	Thickness	inches	7.0	
	Cubic feet		1,903	
	Weight per cubic foot	lbs / cubic foot	3.75	
	Cellulose insulation - RAFTER CAVITIES	by weight	7,136	
	Assumption/Note			

Closed Cell Polyurethane spray foam - BASEMENT WALLS

Ref.	Metric	Calculation	Value	Present Value
	Square feet		1,112	
	Thickness	inches	3.0	
	Cubic feet		278	
	Weight per cubic foot	lbs / cubic foot	2.00	
	Closed Cell Polyurethane spray foam - BASEMENT WALLS	by weight	556	
	Assumption/Note			

Rockwool - BASEMENT WALLS

Ref.	Metric	Calculation	Value	
	Square feet		1,112	
	Thickness	inches	6.0	
	Cubic feet		556	
	Weight per cubic foot	lbs / cubic foot	1.60	
	Rockwool - BASEMENT WALLS	by weight	890	
	Assumption/Note			

Energy Savings if Gas Only

Ref.	Metric	Calculation	Value	
	Annual gas heating utilization - pre DER	Therms	2,766	
	Annual gas heating utilization - post DER	Therms	417.0	
	Annual savings	Therms	2,349	
	Energy Savings if Gas Only		-	
	Assumption/Note			

Energy Savings Estimate - 100 Gallons Oil

Ref.	Metric	Calculation	Value	
	Annual gas heating utilization - pre DER	Gallons	100	
	#4 Oil	Btu	138,700.0	
	Annual savings	Therms	13,870,000	
	Energy Savings Estimate - 100 Gallons Oil		-	
	Assumption/Note			