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Life-Cycle Assessment of the New Jersey Meadowlands Commission Center for Environmental and Scientific Education Building

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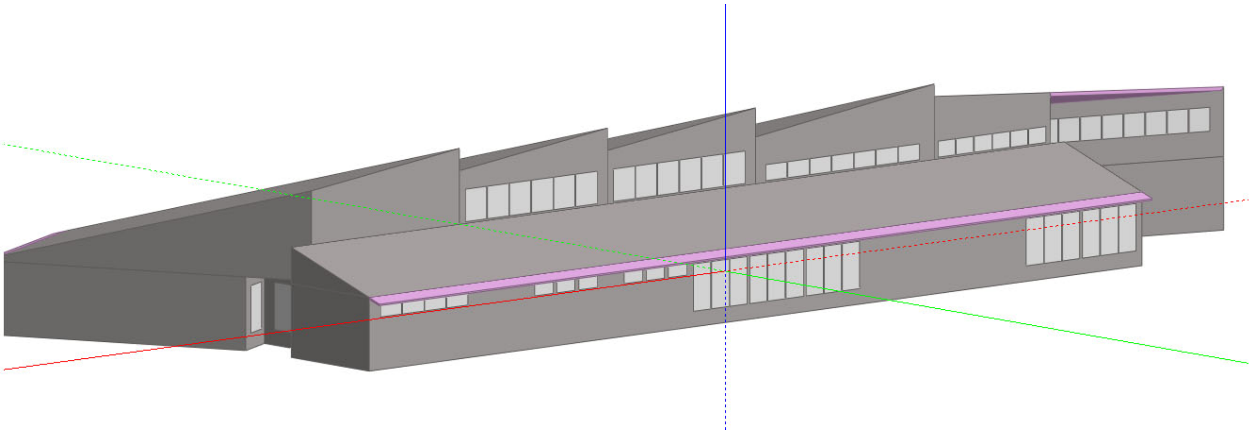

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The Rutgers Center for Green Building (RCGB) is located at the Edward J. Bloustein School of Planning and Public Policy, Rutgers, The State University of New Jersey. The Center works with industry and government to promote green building best practices, and develops undergraduate, graduate and professional education programs. The Center is quickly establishing itself as the pre-eminent interdisciplinary center for green building excellence in the Northeast, while serving as a single accessible locus for fostering collaboration among green building practitioners and policymakers.

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EXECUTIVE SUMMARY

The New Jersey Meadowlands Commission (NJMC) recently completed a new 9,590 sq. ft. educational facility of classrooms, wet chemistry classroom and laboratory, administrative offices, along with an observatory. This building is being certified to Leadership for Energy and Environmental Design (LEED)^{TM} standards, and anticipates at least a LEED Gold rating. To better understand the environmental impacts and benefits from this green building, the NJMC contracted the Rutgers Center for Green Building (RCGB) to conduct a Life Cycle Assessment (LCA) using the building plans and specifications as inputs to the analysis.

Commercial buildings consume approximately 18% of energy and emit 18% of global warming causing gasses in the United States (EIA 2007). The desire to mitigate these environmental and human health impacts has led to an integration of sustainability objectives in building design. A Life Cycle Assessment evaluates the environmental impacts of the building over its entire life cycle including material extraction, manufacturing, transportation, construction, operation and the decommissioning of the building. The whole-building LCA performed here provides insight into the relative impacts of various materials and design choices and of how these impacts may vary across life-cycle phases. The emphasis of this LCA is on primary energy consumption and global warming impacts, but also calculates ozone depletion, acidification, and eutrophication potential. Ozone depletion potential measures the release of chemicals (e.g. refrigerants) that can cause depletion of the ozone layer that protects from UV radiation. Acidification potential calculates air pollutants released to form acids that can harm the ecosystem and buildings. Eutrophication potential measures releases of nutrients that can cause algae bloom in surface water and eventual fish mortalities.

The bottom-line of this LCA is that the impact of the NJMC building on primary energy consumption, global warming potential, and acidification potential is significantly less than that of a conventional building. Most of the building's environmental impact occurs once the building is occupied (operations phase). The environmental impact of the NJMC building during the material placement phase in these same categories – energy, global warming, acidification – exceeds that of a conventional building due to materials used in the foundation, solar cells, concrete foundation caps and floor slab, roof decking and standing seam metal roof. These are offset by savings during the operations phase, reducing the overall impacts of NJMC building when compared to a conventional

building. The decommissioning phase is relatively less important than the materials placement and operations phase as it makes a significantly lower contribution to the impacts.

The environmental impact over the entire life-cycle of the NJMC Center for Environmental and Scientific Education is discussed below. The building has an initial mass of 2052 tons and, including materials for renovations and replacements, 2140 tons. The material placement phase contributes 40.9%, the operations phase 58.1% and the decommissioning phase 1.1% to the total life-cycle primary energy consumption of 8.9×10^3 megawatt hours (MWh). The total life cycle global warming potential of the NJMC Center for Environmental and Scientific Education is 1660 tons of carbon dioxide (CO_2) equivalent (IMPACT 2002+). The materials placement phase contributes 49.6%, the operations phase (electricity from the grid and heating) 48.9% while the decommissioning phase measures only 1.5% of the total life cycle global warming potential.

When normalized on a per-square-foot basis, we can compare these numbers to conventional buildings characterized in the literature. Energy use associated with materials placement for the NJMC Center for Environmental and Scientific Education is 0.47 MWh/ft^2, whereas for conventional buildings found in the literature it is 0.18 MWh/ft^2 (Scheuer et al., 2003) and 0.10 – 0.31 MWh/ft^2 (Cole and Kernan, 1996). However, annual energy use for building operations in the NJMC Center for Environmental and Scientific Education is only 10 kWh/ft^2 (6.5 kWh/ft^2 when solar energy production is netted out) compared to 30.2 kWh/ft^2 for a conventional educational facility in the Mid-Atlantic region (EIA, 2003). Global warming emissions and acidification potential echo this pattern.

Findings for ozone depletion potential and eutrophication potential are less robust because the results are sensitive to methodological nuances. Nonetheless, two notable findings emerge. First, linoleum, which enjoys a reputation as a green material, appears to carry a large eutrophication burden due to the way it is produced. Second, the life cycle ozone depletion potential of the NJMC Center for Environmental and Scientific Education is minimal.

INTRODUCTION

The New Jersey Meadowlands Commission (NJMC) has been charged since its inception with the tasks of balancing economic development and environmental preservation throughout the Meadowlands, as well as with managing the landfill sites located within the Meadowlands. Following through on this mandate, the NJMC has become a leader in environmental conservation by supervising remediation of wetlands, closing landfills to prevent further uncontrolled dumping, initiating programs to capture landfill gas, and developing renewable energy resources for the District to name a few of its efforts.

In this context, when it was determined that existing educational facilities would not meet future demands, the NJMC decided to build to rigorous environmental standards. Specifically, the new NJMC Center for Environmental and Scientific Education was designed and constructed based on the Leadership in Energy and Environmental Design (LEED) standards, developed by the U.S. Green Building Council (USGBC). With the construction of this building, the NJMC has expanded upon its trend-setting role in natural preservation and pollution abatement.

The building under consideration in this study is a 9,590 sq. ft. educational facility with classrooms, and laboratory space. An observatory building, which was constructed simultaneously but is physically separated from the classroom building, has been excluded from consideration in both this Life Cycle Assessment (LCA) and a Life Cycle Cost (LCC) analysis, completed earlier this year for the NJMC. The observatory comprises only 5.5% of the total floor area of the project, and is responsible for very little energy use since it does not contain any office or classroom facilities and is not connected to the Heating, Ventilation, and Air Conditioning (HVAC) system.

A **Life Cycle Assessment** provides an assessment of the environmental impacts of the building over its entire life-cycle. The entire life-cycle of a building includes material extraction, manufacturing, various transportation processes, construction, operation and the decommissioning of the building, whether by recycling and/or disposal. This analysis is accomplished by creating an inventory of **inputs** (raw materials, energy) and **outputs** (atmospheric emissions, waterborne wastes, solid wastes, co-products, and other releases) over the entire life-cycle of the building. The inputs and outputs are converted to **environmental impacts** such as global warming potential, ozone depletion potential and acidification potential, eutrophication and primary energy consumption.

The results of this analysis provide a valuable tool for quantifying the benefits of a green building. Combined with the LCC, this analysis enables a detailed understanding of the environmental impacts associated with the specific choices made in constructing the new NJMC Center for Environmental and Scientific Education. This understanding can be used to guide future policy making regarding the construction of green buildings throughout the Meadowlands, and may prove useful to the U.S. Green Building Council's ongoing evaluation and revision of the LEED Standards.

OBJECTIVES

The objectives of this study are:

- To conduct an LCA of the NJMC Center for Environmental and Scientific Education with a focus on primary energy consumption and global warming potential
- To compare the results with data from the literature

METHODOLOGY

The LCA was conducted in accordance with ISO standards (ISO, 1997; ISO, 1998, ISO, 2000). The majority of the inventory data sets come from the EcoInvent 2.0 database (Frischknecht and Jungbluth, 2007). This database provides energy, material and emissions data for various building materials and components. It covers mainly Swiss and Western European conditions, where LCA work is more common, but recent updates include conditions in other countries (e.g., US energy data). Where appropriate, the energy mix used in Western Europe and Switzerland was replaced with the US or the New Jersey energy mix. Other input data sets came from the Franklin US LCI database (Norris, 2003), the USA Input Output Database 98 database (Suh, 2003), the IDEMAT 2001 database (Remmerswal, 2001) and the Industry 2.0 database which is provided by various industry associations. The other databases were only used if no dataset was found in the Ecoinvent 2.0 database to avoid incompatibilities between databases. The LCA of the NJMC Center for Environmental and Scientific Education was modeled in SimaPro 7.1 (Pre, 2007) which incorporates the previously discussed inventory databases.

Building

The NJMC Center for Environmental and Scientific Education consists of three classrooms, a classroom/laboratory, a wet chemistry laboratory, and administrative offices. The 9,590 sq. ft building commenced operation in April 2008. Building characteristics are provided in Table 1 and a material inventory in Table 2.

Table 1: Building Characteristics

Building System	Specific Characteristics for NJMC Center for Environmental and Scientific Education
Foundation	Chromate copper arsenate treated wood piles (diameter: 7”, length 50’)
Structure	Wood columns (6 1/2” x 6 1/2”), 8” concrete masonry units and glued-laminated wood beams (Forest-Stewardship Council Certified (FSC))
Floors	Cast-in-place reinforced concrete slab
Exterior Walls	Wood studs (FSC, 2” x 6”), DensGlass Gold® exterior sheathing, cement-based siding, glass fiber insulation (U-value: 0.0526 Btu/ft^2 x hr x ^{o}F), gypsum board on interior
Interior Walls	Steel studs, 4 ½” mineral wool, gypsum board on both sides (2 x 5/8” on each side).
Windows and Doors	Windows: vinyl-clad wood windows, double-glazed, argon-filled, low emissivity coating, (U-value 0.349 Btu/ft^2 x hr x ^{o}F), some operable. Doors: exterior aluminum-clad wood-glass doors, interior wood and wood-glass doors.
Roof	Two pitched roofs, offset with north-facing clerestory windows; 20 gauge standing seam galvanized steel roof (SRI value: 69), 2 ½” polyisocyanurate rigid insulation, laminated wood decking (FSC), 2 Solatube skylights per classroom for increased day-lighting, photovoltaic panels on south-facing sections of roof (GEPVp 200 with 54 polycrystalline cells, peak output of 200 W each).
Building Orientation	WSW-ENE axis, with classrooms turned off-axis for maximum (south) solar exposure
Flooring	Linoleum in classrooms and wet chemistry laboratory, linoleum and carpet in laboratory/classroom, carpet tile in offices, terrazzo in common areas
Ceilings	Exposed laminated wood beams and laminated wood decking (FSC).
Lighting	Daylighting and occupancy sensors.
Lighting Controls	Automated lighting controls with manual override
HVAC Heating	8 units, zone separated
HVAC Cooling	8 units, zone separated
HVAC Equipment	8 air handler units (integral Heat/AC units)
HVAC Distribution	Internally insulated round ducts
HVAC Controls	Building automation system with individual classroom and office zone control overrides
Electricity	68% from photovoltaic panels (~ 30% of peak load, electricity return to grid during low load), 32% from external regional utility company (Rutgers Center for Green Building 2008)
Water Heating	Natural gas water heater on site

Table 2: Life-Cycle Mass

Material/Component	Initial Mass [tons]	Life-Cycle Mass* [tons]
Crushed concrete	761.0	761.0
Gravel	390.8	390.8
Sand	305.9	305.9
Cement	118.9	118.9
Wood (FSC)	94.4	94.4
Cold rolled steel)	87.1	93.7
Wood (non-FSC)	59.0	59.0
Light weight concrete blocks	53.8	53.8
Gypsum board	36.6	36.6
Tap water	35.4	35.4
Windows	27.1	54.3
GALVALUME®	18.8	37.7
Lime mortar	10.4	10.4
Terrazzo	7.7	7.7
Fibre cement siding	6.7	6.7
Fiberglass insulation	5.5	5.5
Polyisocuanurate insulation	4.3	8.5
HVAC - furnace & controls	4.0	11.9
Photovoltaic panels	3.1	6.2
Mineral wool insulation	3.0	3.0
Recycled glass	2.8	2.8
Black steel	2.1	2.7
HVAC - cooling	1.8	5.4
Linoleum	1.6	7.9
PVC	1.3	1.9
Exterior aluminum - clad doors	1.0	2.1
Wood preservative	1.0	1.0
Sanitary ceramics	1.0	1.0
Motorized shades	0.8	1.7
Copper	0.8	1.3
Interior wood - glass doors	0.7	1.4
Interior wood doors	0.5	1.1
Polyester	0.5	0.9
Bitumen	0.5	0.9
Paint	0.4	4.4
Polyurethane, flexible foam	0.3	1.4
Light mortar	0.2	0.2
Inverter	0.2	0.7
Zinc, primary	0.1	0.2
Nylon 66	0.1	0.3
Polyester	0.1	0.1
Bitumen	0.1	0.1
Adhesives and sealants	0.1	0.1
Gray cast iron	0.1	0.1
Electrical switches and receptacles	<0.1	<0.1
Glass fibre reinforced plastic	<0.1	<0.1
Stainless steel	<0.1	<0.1
Electronics	<0.1	<0.1
Total	**2052**	**2140**

Environmental Impact Categories

The following standard impact categories have been used to assess the environmental impacts of the NJMC Center for Environmental and Scientific Education: primary energy consumption, global warming potential, acidification potential, ozone depletion potential and eutrophication. Two different environmental impact methods supply the emission factors used in this study to convert the inventory data to environmental impacts: Building for Environmental and Economic Sustainability (BEES) (Lippiatt, 2007, Tables 2.1-2.10) and IMPACT 2002+ (Jolliet et al., 2003, Appendix 1). These two environmental impact methods also include other environmental impacts (e.g. human toxicity, ecotoxicity, land use), but these environmental impacts are not used in this study because they are not as well developed and accepted as the others. The BEES and IMPACT 2002+ methods yield similar results for energy use, global warming, and acidification potentials, but they diverge in their estimates of eutrophication and ozone depletion potentials. The project utilizes both impact methods to test the robustness of the results to nuances of methodology. In cases where the findings are divergent, it is necessary to scrutinize the results more closely for possible explanations.

System Definitions, Boundaries and Data Sources

The life-cycle phases of the NJMC Center for Environmental and Scientific Education are illustrated in Figure 1. The following describes the activities and boundaries for each life-cycle phase. Only the building itself (foundation, structure, envelope, interior) and the retaining wall are included in the LCA. The study utilizes a 50-year building life span estimate provided by the building's architect and for comparison purposes a 75-year life-span. It is assumed that the energy mix and the replacement materials are the same for the entire life cycle of the building. It is believed that this overestimates the environmental impacts, because technological innovations during the life span of the building are expected to reduce the environmental impacts. The following components were excluded from the scope of the analysis: observatory, bathroom supplies, furniture, laboratory equipment, sitework outside the building footprint, landscaping and utilities outside the building. Any impacts that may have resulted from planning and designing the building are also excluded.

The primary energy consumption over the life-cycle of the building in this study was first determined based on the non-renewable energy category as is determined by IMPACT 2002+ (see Appendix 1). An adjustment for the solar energy produced by the building was made subsequently, and comparative values appear later in this report.

Table 3: Environmental Impact Category Emission Factors for BEES (NIST. 1997)

Global Warming	**CO2 (eq.)**	**Acidification**	**H^+ moles (eq./g)**	**Eutrophication**	**N (eq.)**	**Ozone Depletion**	**CFC-11 (eq.)**
Carbon dioxide [a]	1	Ammonia [a]	95.5	Ammonia / Ammonium [a, w]	0.12 - 0.99	CFC-10, Tetrachloromethane [a]	1.1
Carbon dioxide, biogenic [a]	1	Hydrogen chloride [a]	44.7	BOD5, Biological Oxygen Demand [w]	0.05	CFC-12, Dichlorodifluoromethane [a]	1
Carbon dioxide, fossil [a]	1	Hydrogen cyanide [a]	60.4	COD, Chemical Oxygen Demand [w]	0.05	Halon 1001, Bromomethane [a]	0.6
Carbon dioxide, in air [r]	-1	Hydrogen fluoride [a]	81.3	Dinitrogen monoxide [a]	0.092	Halon 1301, Bromotrifluoromethane [a]	10
CFC-10, tetrachloromethane [a]	1800	Hydrogen sulfide [a]	95.9	Nitrate [w]	0.24	HCFC-22, Chlorodifluoromethane [a]	0.055
CFC-12, Dichlorodifluoromethane [a]	10600	Nitrogen oxides, dioxide [a]	40.04	Nitrite [w]	0.32	HCFC-140, 1,1,1-trichloroethane [a]	0.1
CFC-14, Tetrafluoromethane [a]	5700	Sulfur oxides, dioxide [a]	50.8	Nitrogen [w]	0.99		
Chloroform [a]	30	Sulfuric acid [a]	33.3	Nitrogen oxides, monoxide, dioxide [a]	0.044		
Dinitrogen monoxide [a]	296			Phosphate [w]	7.29		
Halon 1001, Bromomethane [a]	5			Phosphoric acid [a]	0.354		
Halon 1301, Bromotrifluoromethane [a]	6900			Phosphorus [a, w]	1.12 - 7.29		
HCFC-22, Chlorodifluoromethane [a]	1700			Phosphorus pentoxide [a, w]	0.489 - 3.18		
HCFC-140, 1,1,1-trichloroethane [a]	140						
Methane [a]	23						
Methane, biogenic [a]	23						
Methane, fossil [a]	23						
Methane, mono- / dichloro- [a]	10 - 16						

Note: (a) air emissions; (r) raw; (s) soil emissions; (w) water emissions.

Material Placement

The material placement phase of a building includes all activities during raw material extraction, refinement of raw materials to engineered materials and manufacturing, various transportation activities during the material placement phase, construction and renovations of the building. The material placement phase also includes avoided activities (impacts) due to use of reused and recycled materials. The list of building materials (Table 2), including for renovations, is based on design specifications, construction cost estimates, final invoices, product submittals, Material Data Safety Sheets, personal communications with the architect and the owner and inquiries of manufacturers and trade organizations.

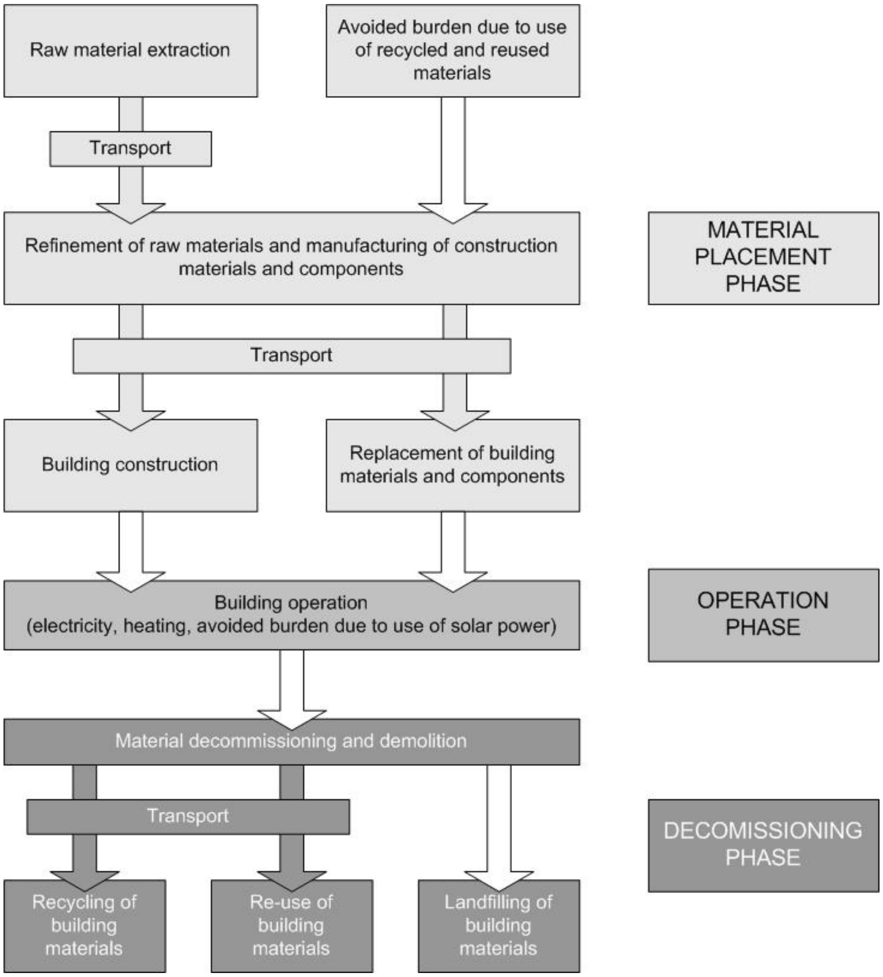


Figure 1: Life Cycle Phases of the NJMC Center for Environmental and Scientific Education.

The inventory associated with material manufacturing is mainly based on the Ecoinvent 2.0 database (Frischknect and Jungbluth, 2007). For materials known to be produced in New Jersey, inputs based on the composition of the New Jersey electricity grid were used. For materials produced in other states of the US, inputs based on an average US electricty grid were used. The energy mix for New Jersey was assumed as follows: coal, 31%, oil, 1%, natural gas, 20%, nuclear, 48% (EIA, 2005). Thirty-one percent of New Jersey's electrical energy is produced in Pennsylvania and 69% in New Jersey. There are material losses during manufacturing and construction. When known, the losses were added to the inventory of materials. If these losses were unknown, a 5% loss was assumed. The replacement frequencies are based on values given in the associated literature (Table 4). Where information on replacement frequencies was unavailable from published sources, estimates were provided by the architect.

Transportation of raw materials to refinement and manufacturing is included in Ecoinvent 2.0. Transportation from the manufacturing facility to the construction site was added. During the construction phase, environmental impacts are caused by electricity use for power tools and lighting, and diesel consumption of heavy equipment. The electricity use was determined by the difference between the 2006 and the 2007 electricity usage records. Diesel consumption of the heavy equipment was included in the analysis (e.g., pile driving equipment).

Table 4: Replacement Frequencies

Building Shell and Structure		Mechanical, Electrical, Plumbing		Building Interior and Finishes	
Component	Years	Component	Years	Component	Years
Treated wood pile foundation	Life[4]	Air ducts	75[3]	Roof wood decking	75[1]
Floor slab	75[1]	Duct insulation	15(75%)[4]	Drywall	75[3]
Structural wood (laminated beams, posts)	75[1]	Drinking water pipes	35(30%)[4]	Interior doors	30[4]
Concrete masonry units	Life[4]	Sewer pipes	35(30%)[4]	Terazzo floor	75[1]
Cement-based siding	50[5]	Natural gas pipes	30(20%)[4]	Bathroom glass tiles	75[1]
DensGlass Gold® exterior sheathing	75[1]	Sprinkler system pipes	35(30%)[4]	Linoleum	10[1]
Thermal wall insulation	75[3]	Methane collection pipes	75[1]	Carpet and carpet tiles	10[1]
Wood studs	75[1]	Sprinkler heads	25[4]	Joint sealer	25[3]
GALVALUME® steel roof	25-30[2]	Bathroom sinks	50[3]	Motorized window shades	25[6]
Roofing insulation	40[4]	Urinals	50[3]	Paint on drywall	5[3]
Exterior doors	40[4]	Toilets	50[3]		
Windows	40[4]	Phone and data wires	25[3]		
Solatube skylights	40[4]	Electrical wires and boxes	25[4]		
		Switches, receptacles	20[1]		
		Galvanized steel conduits	25[1]		
		Air handling unit and controls	20[3]		
		Gas furnace and controls	20[4]		
		Photovoltaic panels	25[1]		
		Flushing valves, toilet and urinal	20[3]		
		Electrical equipment (inverter, transformer, etc.)	20[4]		

[1] Architect (personal communication), [2] GSPNA (2008), [3] Scheuer et al. (2003), [4] Dell'Isola and Kirk (2003), [5] JamesHardie (2008), [6] MechoShade (2008)

Operations Phase

The operations phase activities include heating, cooling and ventilating the building, lighting, and water heating. Since the building is newly constructed, electricity records are not yet available. Therefore, the energy consumption during this phase was modeled using the Design Builder software (DesignBuilder Software Ltd, 2008). Building use characteristics are shown in Table 5.

Table 5: Energy Consumption Details for the NJMC Center for Environmental and Scientific Education

	NJMC Center for Environmental and Scientific Education	Reference
Occupant density, all spaces	0.050 pers/ft^2	ASHRAE Standards
Weather file for energy model	Newark, NJ	Rutgers Center for Green Building (2008)
Schedule of spaces used as offices, classrooms and laboratories	Conditioned 5 am – 9 pm	Rutgers Center for Green Building (2008)
Floor area	9590 ft^2 (861 m^2)	Construction drawings
Internal electrical load (lighting and computers)	2.25 W/ft$^{2\ (}$24 W/m^2)	ASHRAE Standards
Temperature set point, heating	68 ^{o}F (20 ^{o}C)	Rutgers Center for Green Building (2008)
Temperature set back, heating	60 ^{o}F (16 ^{o}C)	Rutgers Center for Green Building (2008)
Temperature set point, cooling	75 ^{o}F (24 ^{o}C)	Rutgers Center for Green Building (2008)
Temperature set back, cooling	82 ^{o}F (28 ^{o}C)	Rutgers Center for Green Building (2008)
Effective leakage area total	2500 in^2 (1.6 m^2)	Rutgers Center for Green Building (2008)
Air exchange modeled	394 cfm/ft^2 (17ft^3/min and pers. fresh air)	ASHRAE Standards

The energy consumption during the operations phase of the building is modeled based on the use and occupancy patterns of the building, the architectural and mechanical features of the building and the local climate. Annual energy consumption is determined as 10 kWh/(ft^2 * yr) (Rutgers Center for Green Building, 2008). According to the Commercial Buildings Energy Consumption Survey (EIA, 2003) educational buildings consume on average 30.2 kWh/(ft^2 * yr). The building has photovoltaic panels on south-facing sections of roof. This reduces the energy consumption to 6.5 kWh/(ft^2 * yr).

Decommissioning Phase

If a building is decommissioned, some building materials and components will be recycled and reused and the rest will be disposed of in a landfill. The owner of the NJMC Center for Environmental and Scientific Education is committed to recycle or reuse as many materials and components of the building as possible. Since it is unknown which building materials and components can be reused and recycled in 50 or 75 years, current practices of the local recycling industry were assumed. Currently, the following building materials and components can be recycled in New Jersey: concrete reinforcement (45%), concrete foundation caps and floor slab (100%), copper electrical wire (100%), galvanized steel conduits (100%), copper pipes (100%), rigid insulated air ducts (100%), carpet tile (100%), concrete masonry unit wall (100%), standing seam metal roof (100%), steel studs (100%) and black steel pipes (100%).

Since the actual energy consumption for the demolition of the NJMC Center for Environmental and Scientific Education is unknown, an average energy consumption of 16.5 MJ/ft^2 for decommissioning was assumed (Scheuer et al. 2003). It was also assumed that all energy was consumed as diesel by the demolition equipment.

In this study, the building's environmental impact is not decreased if a building material or component is recycled or reused in the decommissioning phase. However, the analysis does make an allowance for avoided environmental impact when recycled materials or components are employed during the material placement phase of the building (Figure 1). Since the owner of the building owns landfills no transportation to the landfill was assumed, but transportation to local recycling facilities was taken into account.

RESULTS AND DISCUSSION

The selected environmental impacts, primary energy consumption, global warming potential, acidification potential, ozone depletion potential and eutrophication are discussed below.

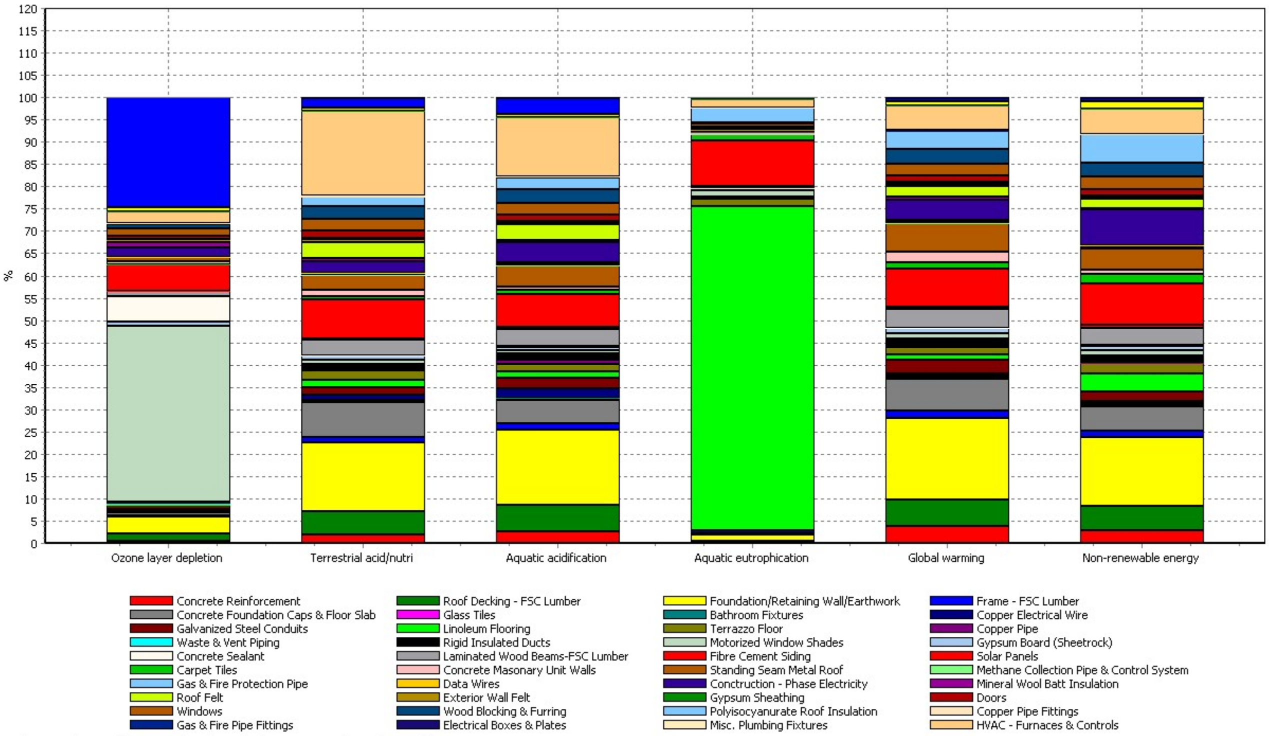
Primary Energy and Materials Consumption (includes Embodied Energy in Materials)

Primary energy is consumed in all three life cycle stages depicted in Figure 1: materials placement phase, operations phase and decommissioning phase. Material consumption takes place mainly in the materials placement phase.

Material Placement

The primary energy consumption in the material placement phase is 3.6 x 10^3 MWh (13 x 10^6 MJ). In addition to the primary energy consumption, many studies determine the embodied energy of the entire building or of individual building materials. The embodied energy includes the primary energy consumption during the materials placement phase plus the feedstock energy of the materials (= higher heating value of the materials). Many building materials are non-combustible and the feedstock energy can be estimated to be negligible. Only wood, linoleum, PVC and polyisocyanurate insulation have a mass of more than 1 ton in the NJMC Center for Environmental and Scientific Education and are combustible (Table 2). The major portions of the windows and the HVAC – cooling unit are non-combustible and therefore are not included in this estimation. Assuming a higher heating value of 4.93 MWh/ton (19.55 GJ/metric tonne) for wood (Demirba, 2001), 4.69 MWh/ton (18.6 GJ/metric tonne) for linoleum (GreenFloors, 2008), 5.04 MWh/ton (20 GJ/metric tonne) for flexible PVC (Menke et al., 2003) and 6.55 MWh/ton (26 GJ/metric tonne) for polyisocyanurate insulation, the embodied energy in the NJMC Center for Environmental and Scientific Education can be estimated as 4.5 x 10^3 MWh (13 x 10^6 MJ + 3.1 x 10^6 MJ = 16.1 x 10^6 MJ) Taking the square footage into account, this equals 0.47 MWh/ft^2 (17.9 GJ/m^2), which exceeds the values found in the literature (0.18 MWh/ft^2 (7.0 GJ/ m^2, Scheuer et al., 2003), 0.10 – 0.31 MWh/ft^2 (4-12 GJ/m^2, Cole and Kernan, 1996)). However, a higher embodied energy in the NJMC Center for Environmental and Scientific Education is not unexpected for a green building that employs more sophisticated materials and technologies than a conventional building.

In particular, main contributors to primary energy during the materials placement phase are the foundation, the solar cells, the concrete foundation caps and the floor slab, the roof decking, the standing seam metal roof, the construction phase electricity, the polyisocyanurate roof insulation and the HVAC - furnaces and controls. (Figure 2 and Appendix 2).



Analyzing 1 p 'Material Placement Phase'; Method: IMPACT 2002+ (NJMC) V2.03 / characterization

Figure 2: Distribution of the Environmental Impacts during the Materials Placement Phase (IMPACT 2002+).

The initial mass in the NJMC Center for Environmental and Scientific Education is 2052 tons (Table 2). Taking into account 88 tons of replacement materials, the total life cycle mass is 2140 tons. Crushed concrete as porous fill under the slab has the highest mass with 37.1%, followed by 19.0%, 14.9% and 5.8% for the concrete ingredients gravel, sand and cement. The next largest mass is the Forest Stewardship Council-certified (FSC) wood with 4.6% and the steel with 4.2% which can be mostly found in the sheet pile wall and the reinforcement of the slab. The next highest masses are the non-FSC wood with 2.9%, the concrete blocks with 2.6%, the gypsum board with 1.8%, tap water with 1.7% and windows with 1.3%. All other components together contribute less than 4.1% to the total mass of the building.

The replacement materials account only for a small portion of the life cycle mass of the building (4%). Even though the embodied energy of individual materials was not determined in this study, it is expected that materials with higher replacement frequencies such as carpets or copper wires have higher embodied energies than materials with lower replacement frequencies such as sand, gravel and cement as shown by Scheuer et al. (2003).

Operations Phase

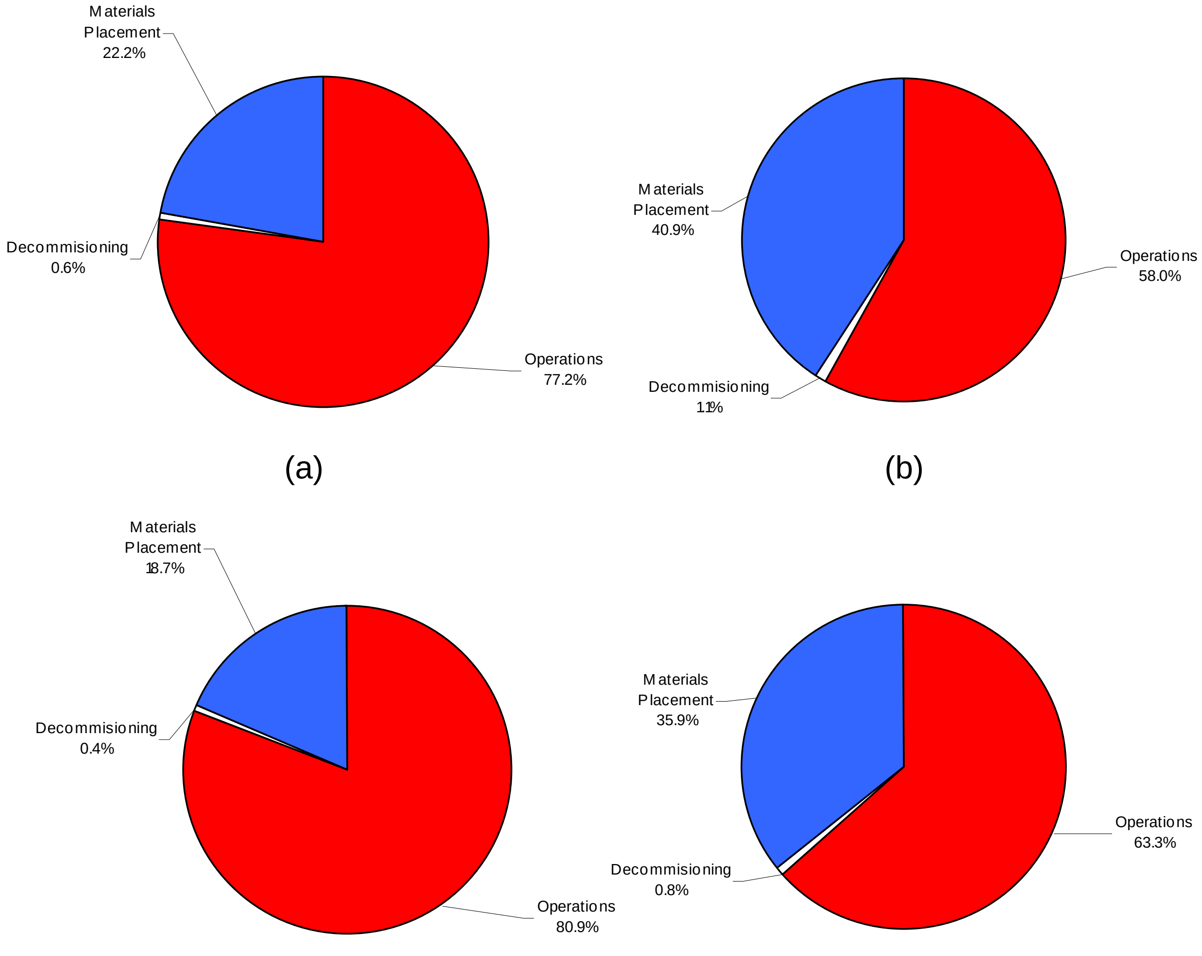
Based on the LCC (Rutgers Center for Green Building, 2008), the energy intensity of the NJMC Center for Environmental and Scientific Education is much lower than the energy intensity of conventional educational buildings. Due to the improved energy efficiency (e.g., daylighting, improved insulation), the energy intensity of the NJMC Center for Environmental and Scientific Education is 10 kWh/ft^2 compared to an average educational facility with 30.2 kWh/ft^2 (2003 Commercial Buildings Energy Consumption Building Survey (EIA, 2003)). If the energy intensity of the NJMC Center for Environmental and Scientific Education is reduced by the solar energy as a credit for the reduced energy consumption from the grid, the energy intensity of the NJMC Center for Environmental and Scientific Education would be 6.5 kWh/ft^2.

As a result of both building energy efficiency measures and the inclusion of renewable solar energy, the operations phase is less dominant in the total life cycle primary energy consumption than would otherwise be the case. However, the operations phase is still an important phase in the life cycle primary energy consumption of the building, as with other buildings that have been studied.

In the hypothetical case that the NJMC Center for Environmental and Scientific Education does not have solar panels and giving a credit for the reduced energy consumption from the grid, the operations phase (12.6 x 10^3 MWh (45.3 x 10^6 MJ)) would contribute 77.2% to the total life cycle primary energy consumption (16.3 x 10^3 MWh (58.7 x 10^6 MJ) (Figure 3).. For comparison, a classroom and hotel building at the University of Michigan consumes 97.7% of the life cycle energy for the building operation (Scheuer et al., 2003). This difference most likely can be attributed to the energy efficiency of the NJMC Center for Environmental and Scientific Education.

In the actual NJMC Center for Environmental and Scientific Education with solar panels and a credit for the reduced energy consumption, the operations phase (5.1 x 10^3 MWh (18.5 x 10^6 MJ)) contributes 58.1% to the total life cycle primary energy consumption (8.9 x 10^3 MWh (31.9 x 10^6 MJ)) (Figure 3).

In a second hypothetical case, the building life span is extended from 50 to 75 years. The differences are minor. As built (with solar panels), primary energy consumption during the operations phase increases from 58.1% to 63.3% of total primary energy consumption across the entire lifecycle of the building.



(a) (b)

(c) (d)

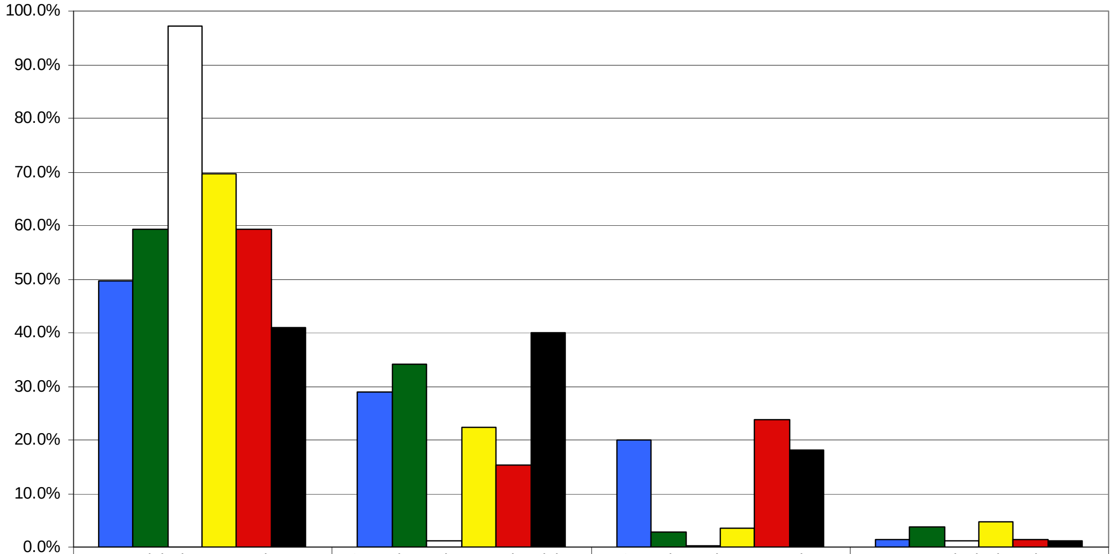
Figure 3: Distribution of the life cycle primary energy consumption for 50-year building life (a) without credit for solar power and (b) with credit for solar power, and 75-year building life (c) without credit for solar power and (d) with credit for solar power.

Decommissioning Phase

As found in other studies, the decommissioning phase (1.1%) has a low impact compared to the other two life cycle phases, the materials placement phase and the operations phase. This confirms findings by Scheuer et al. (2003).

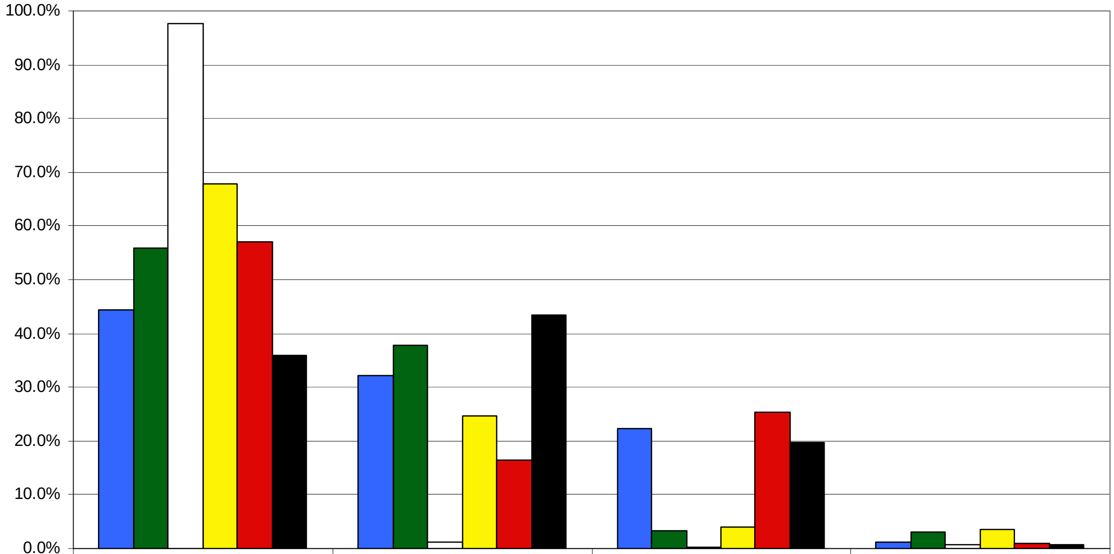
Global Warming Potential (GWP)

The total life cycle GWP of the NJMC Center for Environmental and Scientific Education is 1660 tons of CO_2 equivalent (1500 metric tonnes) based on the IMPACT 2002+ impact method and 1710 tons of CO_2 equivalent (1550 metric tonnes) equivalent based on the BEES impact method. This GWP is reduced by the GWP of the electrical energy that is equivalent to the solar energy that is given back to the grid. As expected, the life cycle GWP is largely determined by and therefore closely matches the life cycle primary energy consumption (Figure 4, Figure 5 and Appendix 2). In other words, the NJMC Center for Environmental and Scientific Education has a slightly higher global warming potential as compared to a conventional building in analyzing only the materials placement phase of the building life cycle. Main contributors to the primary energy consumption in the materials placement phase are the foundation, the solar cells, the concrete foundation caps and the floor slab, the roof decking, the standing seam metal roof, the construction phase electricity, the polyisocyanurate roof insulation and the HVAC - furnaces and controls. (Figure 2). The slight increase in GWP that results is more than compensated for in the operations phase of the building life cycle, wherein the NJMC Center for Environmental and Scientific Education has a markedly lower global warming potential than a conventional building. The operations phase (electricity from the grid and heating) contributes 48.9% according to IMPACT 2002+ impact method and 50.0% according to the BEES impact method to total life cycle GWP.



	Material Placement Phase	Operations Phase - Electricity	Operations Phase - Heating	Decommissioning Phase
🟦 GWP	49.6%	28.9%	20.0%	1.5%
🟩 AAP	59.2%	34.1%	2.9%	3.8%
☐ ANP	97.3%	1.3%	0.2%	1.2%
🟨 TA/NP	69.5%	22.2%	3.5%	4.7%
🟥 OD	59.4%	15.3%	23.9%	1.5%
■ NRE	40.9%	39.9%	18.2%	1.1%

(a)

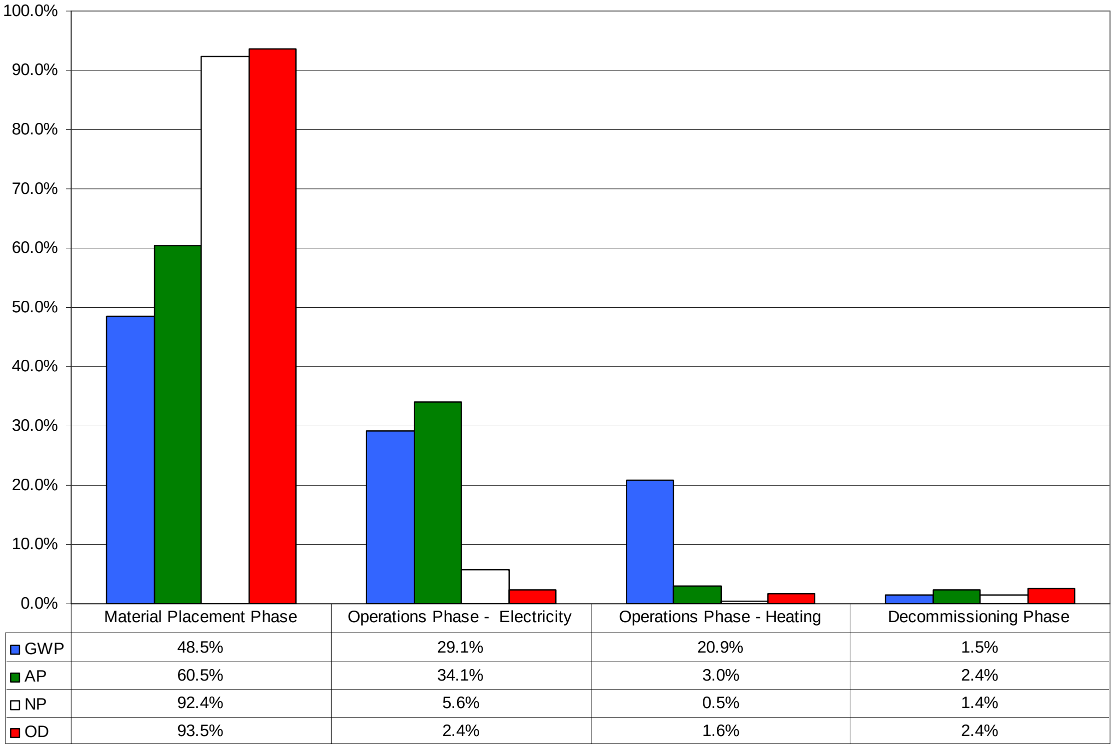


	Material Placement Phase	Operations Phase - Electricity	Operations Phase - Heating	Decommissioning Phase
🟦 GWP	44.3%	32.2%	22.4%	1.1%
🟩 AAP	55.9%	37.8%	3.2%	3.0%
☐ ANP	97.7%	1.3%	0.2%	0.8%
🟨 TA/NP	67.9%	24.7%	3.9%	3.5%
🟥 OD	57.1%	16.3%	25.5%	1.1%
■ NRE	35.9%	43.5%	19.8%	0.8%

(b)

(GWP – Global Warming Potential, AAP – Aquatic Acidification Potential, ANP – Aquatic Eutrophication, TA/NP – Terrestrial acidification/nitrification, OD – Ozone Depletion, NRE - Non—Renewable Energy)

Figure 4: Distribution of selected environmental impacts based on IMPACT 2002+ for (a) 50-year building life and (b) 75-year building life



	Material Placement Phase	Operations Phase - Electricity	Operations Phase - Heating	Decommissioning Phase
🟦 GWP	48.5%	29.1%	20.9%	1.5%
🟩 AP	60.5%	34.1%	3.0%	2.4%
☐ NP	92.4%	5.6%	0.5%	1.4%
🟥 OD	93.5%	2.4%	1.6%	2.4%

GWP – Global Warming Potential, AP –Acidification Potential, NP – Eutrophication, OD – Ozone Depletion)

Figure 5: Distribution of selected environmental impacts based on BEES 4.0

In the sensitivity analysis comparing a 50-year building life span to a 75-year life span, global warming potential impacts attributed to various phases of the building life cycle did not exhibit a significant change. As may be noted in Figure 3b, the global warming potential impacts of the material placement phase drops about 5% compared to overall impacts, and this was the greatest change. Operations phase electricity increases its share of global warming impacts by about 3%, while heating increases by less than 2%. The sensitivity analysis only utilizes the IMPACT2002+ methodology as the results with BEES 4.0 are similar.

Ozone Depletion

The total life cycle ozone depletion of the NJMC Center for Environmental and Scientific Education is 0.47 lb of CFC-11 equivalent (213 g) based on the IMPACT 2002+ impact method and 0.23 lb of CFC-11 equivalent (106 g) based on the BEES 4.0 impact method. This ozone depletion potential is reduced by the ozone depletion potential of the electrical energy that is equivalent to the solar energy that is given back to the grid. This is generally a very low ozone depletion potential over the life-time of the building. While the materials placement phase contributes 93.5% based on the BEES 4.0 impact method (Figure 5), this phase only contributes 59.4 % based on the IMPACT 2002+ (Figure 4). The IMPACT 2002+ impact accounts for more compounds contributing to the ozone depletion potential. A large portion of the ozone depletion potential based on IMPACT 2002+ is CFC-114 that is used during uranium enrichment, but CFC-114 is not included as a substance in the BEES 4.0 impact method (Table 3 and Appendix 1). As a result, the operational phase makes a significant contribution to the life cycle ozone depletion based on the IMPACT 2002+ impact method. For the materials placement phase, the motorized window shades, the concrete sealant, the fibre cement siding and the HVAC – cooling unit are major contributors.

Eutrophication

While the IMPACT 2002+ impact method assesses the aquatic eutrophication impacts in a phosphorus limited watershed, the BEES 4.0 impact assessment addresses watersheds that are also affected by nitrogen releases to water, land and air. The IMPACT 2002+ covers the nitrogen releases to air under a separate environmental impact (Terrestrial Acidification/Nutrification, see below). As the result, the eutrophication impacts assessed by these two methods differ.

The total life cycle aquatic eutrophication of the NJMC Center for Environmental and Scientific Education is 333 lb (151 kg) of phosphorus (PO_4) equivalent based on the IMPACT 2002+ impact method and 4256 lb (1930 kg) of nitrogen (N) equivalent based on the BEES 4.0 impact method. These total life cycle impacts account for the reduction of electrical energy consumption from the grid due to the solar power. While based on IMPACT 2002+ the materials placement contributes 97.3 % to the aquatic eutrophication (Figure 4), this phase contributes 92.4% to eutrophication based on the BEES 4.0 impact method (Figure 5).

The linoleum flooring is the dominant contributor of eutrophication impacts to the materials phase of the building's life cycle. A significant portion of the nitrogen and phosphorus applied to the agricultural fields to grow flax, one of the raw materials for the linoleum, is released as non-point pollution. The release of the fertilizer to the environment is responsible for the eutrophication impacts.

Acidification

The total life cycle *aquatic* acidification for the NJMC Center for Environmental and Scientific Education is 10.2 tons (9.2 metric tonnes) of sulfur dioxide (SO_2) equivalent, and the total life cycle *terrestrial* acidification/nitrification is 33.5 tons (30.4 metric tonnes) of SO_2 equivalent, according to the IMPACT 2002+ methodology. According to the BEES 4.0 methodology, the total life cycle acidification is 528 (479 metric tonnes) of hydrogen ion (H+) ton moles equivalent. These acidification impacts account for the reduction of electrical energy consumption from the grid due to the solar power. All acidification impacts match the distribution of the primary life cycle energy consumption impact and the global warming potential impact (Figure 4 and 5). Also, the acidification contribution of the different materials in the materials phase matches the findings for primary energy consumption and global warming potential (Figure 2).

SUMMARY AND CONCLUSIONS

The LCA of the NJMC Center for Environmental and Scientific Education provides an assessment of the environmental impacts of the building over its entire life cycle. The life cycle includes the materials placement phase (material extraction, manufacturing, various transportation processes, construction of the building), the operations phase and the decommissioning phase (recycling, reuse and disposal of the building). An inventory of materials, energy and emissions over the entire life cycle of the building was determined mainly based on design specifications, construction plans and construction cost estimates of the NJMC Center for Environmental and Scientific Education and utilizing life cycle assessment databases. Based on these data, the following environmental impacts were modeled using the BEES 4.0 and IMPACT 2002+ methods: primary energy consumption, global warming potential, acidification, eutrophication and ozone depletion potential.

The LCA was successful in evaluating life cycle energy related aspects of the NJMC Center for Environmental and Scientific Education. The NJMC Center for Environmental and Scientific Education has an initial mass of 2052 tons and of 2140 tons if materials for renovations and replacements are included. The material placement phase contributes 40.9%, the operations phase 58.1% and the decommissioning phase 1.1% to the total life-cycle primary energy consumption of 8.9 x 10^3 MWh. The LCA showed that the life cycle primary energy consumption of the NJMC Center for Environmental and Scientific Education is much less dominated by the operations phase than in conventional buildings, due to the energy efficiency of the NJMC Center for Environmental and Scientific Education and the solar panels. However, the embodied primary energy during the materials placement phase seems to be higher than in conventional buildings. The decommissioning phase is of less importance compared to the other two life cycle phases when assessing the life cycle primary energy consumption. Similar effects as found for the life cycle primary energy consumption were also found for the global warming potential and the acidification potential. The total life cycle global warming potential of the NJMC Center for Environmental and Scientific Education is 1660 tons of CO_2 equivalent (IMPACT 2002+). The materials phase contributes 49.6%, the operations phase (electricity from the grid and heating) 48.9% and the decommissioning phase 1.5% to the total life cycle global warming potential.

For the environmental impacts closely associated with the non-renewable energy consumption (primary energy consumption, global warming potential and acidification) the results modeled by BEES 4.0 and IMPACT 202+ agree well. However for other environmental impacts such as ozone depletion potential and eutrophication, the results differ because different inventory data are assessed by the different methods. For example, eutrophication in IMPACT 2002+ focuses on a phosphorus-limited watershed and does not include the nitrogen compounds in the impact assessment.

The LCA also highlights how building material choices may inadvertently shift impacts across impact categories and/or geographies (e.g., the eutrophication effects of linoleum). This was confirmed by other studies that compared wood, linoleum and PVC flooring materials and concluded that wood flooring is the most favorable floor material followed by linoleum and then PVC (Jönsson et al., 1995). However, wood flooring is the most expensive flooring material.

The NJMC Center for Environmental and Scientific Education uses FSC and non-FSC wood as major building materials in the foundation, the structure and the frame of the building. The FSC wood was modeled as non-FSC wood because the datasets to model FSC wood are not yet available. However, it is not evident that there would be many differences concerning the environmental impacts that were addressed in this study. It is expected that further research will show that the major difference between the use of FSC and non-FSC wood will be more closely tied to land use and management (USGBC MR TAG, 2007) than resource consumption. For example, though FSC's Principles and Criteria (FSC, 1996) do not preclude the use of chemicals (only ones that have been deemed hazardous are to be avoided), logging practices are required to maintain the integrity of the forest ecosystem—a significant environmental benefit that is not easily quantified using existing LCA techniques.

In closing, this life-cycle assessment confirms that the new NJMC Center for Environmental and Scientific Education has a relatively light environmental footprint compared to a conventional building. This study highlights the importance of design choices in determining environmental impacts during materials placement, operation, and decommissioning of buildings. It shows that choices imposing higher impacts during the materials placement phase can yield dramatically lower impacts during operation. These findings are indicative of the benefits builders can expect from green building practices.

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APPENDICES

Environmental impact category emission factors for IMPACT 2002+

Global warming	**CO_2 (kg)**	**Aquatic acidification**	**SO_2 (kg)**	**Aquatic eutrophication**	**PO_4-Plim (kg)**	**Terrestrial acid/nutrification**	**SO_2 (kg)**
1-Propanol, 3,3,3-trifluoro-2,2-bis(trifluoromethyl)-, HFE-7100 [a]	120	Ammonia [a, w]	1.88	Ammonia [a, w, s]	0	Ammonia [a]	15
1H,1H,2H,2H-Perfluorohexan-1-ol, HFE-7200 [a]	17	Ammonia, as N [a, w]	2.28	Ammonium, ion [a, w, s]	0	Nitric oxide [a]	8.44
Butane, 1,1,1,3,3-pentafluoro-, HFC-365mfc [a]	280	Hydrogen chloride [a, w, s]	0.88	COD, Chemical Oxygen Demand [a, w, s]	0.022	Nitrogen dioxide [a]	5.49
Butane, perfluoro- [a]	12400	Hydrogen fluoride [a, w, s]	1.6	Nitrate [a]	0	Nitrogen oxides [a]	5.49
Butane, perfluorocyclo-, PFC-318 [a]	14500	Hydrogen sulfide [a, w, s]	1.88	Nitric acid [a, w, s]	0	Sulfur dioxide [a]	1
Carbon dioxide [a]	1	Nitrate [a]	0.5	Nitric oxide [a]	0	Sulfur oxides [a]	1
Carbon dioxide, biogenic [a]	0	Nitric acid [a, w, s]	0.51	Nitrite [a, w]	0	Sulfur trioxide [a]	0.8
Carbon dioxide, fossil [a]	1	Nitric oxide [a]	1.07	Nitrogen [a, w, s]	0		
Carbon monoxide [a]	1.57	Nitrite [a]	0.7	Nitrogen dioxide [a]	0		
Carbon monoxide, biogenic [a]	0	Nitrogen dioxide [a]	0.7	Nitrogen oxides [a]	0		
Carbon monoxide, fossil [a]	1.57	Nitrogen oxides [a]	0.7	Nitrogen, total [a, w, s]	0		
Chloroform [a]	9	Phosphoric acid [a, w, s]	0.98	Phosphate [a, w, s]	1		
Dimethyl ether [a]	1	Sulfur dioxide [a]	1	Phosphoric acid [a, w, s]	0.97		
Dinitrogen monoxide [a]	156	Sulfur oxides [a]	1	Phosphorus [a, w, s]	3.06		
Ethane, 1-chloro-1,1-difluoro-, HCFC-142b [a]	740	Sulfur trioxide [a]	0.8	Phosphorus pentoxide [a, w, s]	1.34		
Ethane, 1-chloro-2,2,2-trifluoro-(difluoromethoxy)-, HCFE-235da2 [a]	110	Sulfuric acid [a, w, s]	0.65	Phosphorus, total [a, w, s]	3.06		
Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b [a]	220						
Ethane, 1,1-difluoro-, HFC-152a [a]	37						
Ethane, 1,1,1-trichloro-, HCFC-140 [a]	42						
Ethane, 1,1,1-trifluoro-, HFC-143a [a]	1600						
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a [a]	400						
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113 [a]	2700						
Ethane, 1,1,2-trifluoro-, HFC-143 [a]	100						
Ethane, 1,1,2,2-tetrafluoro-, HFC-134 [a]	330						
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114 [a]	8700						
Ethane, 1,2-difluoro-, HFC-152 [a]	13						

Environmental Impact Category Emission Factors for 2002+ (cont.)

Global warming	**CO2 (kg)**	**Aquatic acidification**	**SO_2 (kg)**	**Aquatic eutrophication**	**PO_4-Plim (kg)**	**Terrestrial acid/nutrification**	**SO_2 (kg)**
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124 [a]	190						
Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123 [a]	36						
Ethane, chloropentafluoro-, CFC-115 [a]	9900						
Ethane, fluoro-, HFC-161 [a]	4						
Ethane, hexafluoro-, HFC-116 [a]	18000						
Ethane, pentafluoro-, HFC-125 [a]	1100						
Ethanol, 2,2,2-trifluoro- [a]	18						
Ether, 1,1,1-trifluoromethyl methyl-, HFE-143a [a]	230						
Ether, 1,1,2,2-Tetrafluoroethyl 2,2,2-trifluoroethyl-, HFE-347mcf2 [a]	150						
Ether, 1,1,2,2-Tetrafluoroethyl methyl-, HFE-254cb2 [a]	9						
Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcf3 [a]	130						
Ether, di(difluoromethyl), HFE-134 [a]	2000						
Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245cb2 [a]	180						
Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245fa2 [a]	180						
Ether, ethyl 1,1,2,2-tetrafluoroethyl-, HFE-374pc2 [a]	170						
Ether, pentafluoromethyl-, HFE-125 [a]	9200						
H-Galden 1040x [a]	560						
Hexane, perfluoro- [a]	13200						
HG-01 [a]	450						
HG-10 [a]	850						
Methane [a]	7						
Methane, biogenic [a]	0						
Methane, bromo-, Halon 1001 [a]	1						
Methane, bromochlorodifluoro-, Halon 1211 [a]	390						
Methane, bromodifluoro-, Halon 1201 [a]	150						

Environmental Impact Category Emission Factors for 2002+ (cont.)

Global warming	**CO2 (kg)**	**Aquatic acidification**	**SO_2 (kg)**	**Aquatic eutrophication**	**PO_4- Plim (kg)**	**Terrestrial acid/nutrification**	**SO_2 (kg)**
Methane, bromotrifluoro-, Halon 1301 [a]	2700						
Methane, chlorodifluoro-, HCFC-22 [a]	540						
Methane, chlorotrifluoro-, CFC-13 [a]	16300						
Methane, dibromo- [a]	1						
Methane, dichloro-, HCC-30 [a]	3						
Methane, dichlorodifluoro-, CFC-12 [a]	5200						
Methane, dichlorofluoro-, HCFC-21 [a]	65						
Methane, difluoro-, HFC-32 [a]	170						
Methane, fluoro-, HFC-41 [a]	30						
Methane, fossil [a]	7						
Methane, iodotrifluoro- [a]	1						
Methane, monochloro-, R-40 [a]	5						
Methane, tetrachloro-, CFC-10 [a]	580						
Methane, tetrafluoro-, CFC-14 [a]	8900						
Methane, trichlorofluoro-, CFC-11 [a]	1600						
Methane, trifluoro-, HFC-23 [a]	10000						
Pentane, 2,3-dihydroperfluoro-, HFC-4310mee [a]	470						
Pentane, perfluoro- [a]	13200						
Propane, 1,1,1,2,2,3-hexafluoro-, HFC-236cb [a]	390						
Propane, 1,1,1,2,3,3-hexafluoro-, HFC-236ea [a]	390						
Propane, 1,1,1,2,3,3,3-heptafluoro-, HFC-227ea [a]	1100						
Propane, 1,1,1,3,3-pentafluoro-, HFC-245fa [a]	300						
Propane, 1,1,1,3,3,3-hexafluoro-, HCFC-236fa [a]	7100						
Propane, 1,1,2,2,3-pentafluoro-, HFC-245ca [a]	200						
Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb [a]	190						
Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca [a]	55						
Propane, perfluoro- [a]	12400						
Propanol, 1,1,1,3,3,3-hexafluoro-2- [a]	59						

Environmental Impact Category Emission Factors for 2002+ (cont.)

Global warming	**CO2 (kg)**	**Aquatic acidification**	**SO_2 (kg)**	**Aquatic eutrophication**	**PO_4-Plim (kg)**	**Terrestrial acid/nutrification**	**SO_2 (kg)**
Propanol, pentafluoro-1- [a]	13						
Sevoflurane [a]	100						
Sulfur hexafluoride [a]	32400						

Note: (a) air emissions; (r) raw; (s) soil emissions; (w) water emissions.

Environmental Impact Category Emission Factors for 2002+ (cont.)

Ozone layer depletion	**CFC-11 (kg)**	**Non-renewable energy**	**MJ PRIMARY**
Ethane, 1-bromo-1,1-difluoro- [a]	0.47	Coal, 18 MJ per kg, in ground [r]	18
Ethane, 1-bromo-1,1,2,2-tetrafluoro- [a]	0.92	Coal, 26.4 MJ per kg, in ground [r]	26.4
Ethane, 1-bromo-2-fluoro-, FC-151b1 [a]	0.084	Coal, 29.3 MJ per kg, in ground [r]	29.3
Ethane, 1-chloro-1,1-difluoro-, HCFC-142b [a]	0.07	Coal, brown (lignite) [r]	9.9
Ethane, 1,1-dibromo-2,2-difluoro- [a]	0.55	Coal, brown, 10 MJ per kg, in ground [r]	10
Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b [a]	0.12	Coal, brown, 8 MJ per kg, in ground [r]	8
Ethane, 1,1,1-trichloro-, HCFC-140 [a]	0.12	Coal, brown, in ground [r]	9.9
Ethane, 1,1,1-trifluoro-2-bromo- [a]	1.1	Coal, feedstock, 26.4 MJ per kg, in ground [r]	26.4
Ethane, 1,1,1-trifluoro-2,2-chlorobromo-, Halon 2311 [a]	0.14	Coal, hard, unspecified, in ground [r]	19.1
Ethane, 1,1,1,2-tetrafluoro-2-bromo-, Halon 2401 [a]	0.92	Energy, from coal [r]	1
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113 [a]	1	Energy, from coal, brown [r]	1
Ethane, 1,1,2,2-tetrachloro-1-fluoro-, HCFC-121 [a]	0.02	Energy, from gas, natural [r]	1
Ethane, 1,1,2,2-tetrachloro-1,2-difluoro-, CFC-112 [a]	1	Energy, from oil [r]	1
Ethane, 1,2-dibromo-1-fluoro- [a]	0.41	Energy, from uranium [r]	1
Ethane, 1,2-dibromo-1,1-difluoro- [a]	0.55	Energy, unspecified [r]	1
Ethane, 1,2-dibromo-1,1,2-trifluoro- [a]	0.8	Gas, natural (0,8 kg/m3) [r]	40.3
Ethane, 1,2-dibromotetrafluoro-, Halon 2402 [a]	8.6	Gas, natural, 30.3 MJ per kg, in ground [r]	30.3
Ethane, 1,2-dichloro-1,1-difluoro-, HCFC-132b [a]	0.02	Gas, natural, 35 MJ per m3, in ground [r]	35
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114 [a]	0.94	Gas, natural, 36.6 MJ per m3, in ground [r]	36.6
Ethane, 2-bromo-1,1-difluoro- [a]	0.47	Gas, natural, 46.8 MJ per kg, in ground [r]	46.8
Ethane, 2-chloro-1,1,1-trifluoro-, HCFC-133a [a]	0.035	Gas, natural, feedstock, 35 MJ per m3, in ground [r]	35
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124 [a]	0.02	Gas, natural, feedstock, 46.8 MJ per kg, in ground [r]	46.8
Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123 [a]	0.02	Gas, natural, in ground [r]	40.3
Ethane, chloropentafluoro-, CFC-115 [a]	0.44	Gas, petroleum, 35 MJ per m3, in ground [r]	35
Ethane, pentachlorofluoro-, CFC-111 [a]	1	Methane [r]	50.4
Ethane, tetrabromofluoro- [a]	0.49	Oil, crude, 38400 MJ per m3, in ground [r]	38400
Ethane, tribromodifluoro- [a]	0.95	Oil, crude, 41 MJ per kg, in ground [r]	41
Ethane, tribromofluoro- [a]	0.33	Oil, crude, 42 MJ per kg, in ground [r]	42
Ethane, trichlorodifluoro-, HCFC-122 [a]	0.04	Oil, crude, 42.6 MJ per kg, in ground [r]	42.6
Ethane, trichlorofluoro-, HCFC-131 [a]	0.019	Oil, crude, 42.7 MJ per kg, in ground [r]	42.7
Methane, bromo-, Halon 1001 [a]	0.38	Oil, crude, feedstock, 41 MJ per kg, in ground [r]	41
Methane, bromochlorodifluoro-, Halon 1211 [a]	6	Oil, crude, feedstock, 42 MJ per kg, in ground [r]	42
Methane, bromodifluoro-, Halon 1201 [a]	0.74	Oil, crude, in ground [r]	45.8
Methane, bromofluoro- [a]	0.73	Peat, in ground [r]	9.9
Methane, bromotrifluoro-, Halon 1301 [a]	12	Uranium ore, 1.11 GJ per kg, in ground [r]	1110
Methane, chlorobromo-, Halon 1011 [a]	0.12	Uranium, 2291 GJ per kg, in ground [r]	2290000
Methane, chlorodifluoro-, HCFC-22 [a]	0.05	Uranium, 451 GJ per kg, in ground [r]	451000
Methane, chlorofluoro-, HCFC-31 [a]	0.02	Uranium, 560 GJ per kg, in ground [r]	560000
Methane, chlorotrifluoro-, CFC-13 [a]	1	Uranium, in ground [r]	560000
Methane, dibromofluoro-, HBFC-22B1 [a]	1	Wood (16.9 MJ/kg) [r]	0
Methane, dichlorodifluoro-, CFC-12 [a]	1	Wood, hard, standing [r]	0
Methane, dichlorofluoro-, HCFC-21 [a]	0.04	Wood, soft, standing [r]	0

Environmental Impact Category Emission Factors for 2002+ (cont.)

Methane, monochloro-, R-40 [a]	0.02	Wood, unspecified, standing/m3 [r]	0
Methane, tetrachloro-, CFC-10 [a]	0.73		
Methane, trichlorofluoro-, CFC-11 [a]	1		
Propane, 1-bromo-1,1,2,3,3,3-hexafluoro- [a]	1.5		
Propane, 1-bromo-2-fluoro- [a]	0.12		
Propane, 1-bromo-3-fluoro- [a]	0.12		
Propane, 1,2,2-tribromo-3,3,3-trifluoro- [a]	1.1		
Propane, 1,2,3-tribromo-3,3-difluoro- [a]	0.56		
Propane, 1,3-dibromo-1,1-difluoro- [a]	0.32		
Propane, 1,3-dibromo-1,1,3,3-tetrafluoro- [a]	1.5		
Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb [a]	0.03		
Propane, 2,3-dibromo-1,1,1-trifluoro- [a]	0.5		
Propane, 3-bromo-1,1,1-trifluoro- [a]	0.24		
Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca [a]	0.02		
Propane, bromodifluoro- [a]	0.24		
Propane, bromopentafluoro- [a]	1.1		
Propane, bromotetrafluoro- [a]	1.1		
Propane, chloroheptafluoro-, CFC-217 [a]	1		
Propane, dibromofluoro- [a]	0.13		
Propane, dibromopentafluoro- [a]	1.3		
Propane, dichlorodifluoro-, HCFC-252 [a]	0.014		
Propane, dichlorofluoro-, HCFC-261 [a]	0.0063		
Propane, dichlorohexafluoro-, CFC-216 [a]	1		
Propane, dichlorotetrafluoro-, HCFC-234 [a]	0.053		
Propane, dichlorotrifluoro-, HCFC-243 [a]	0.029		
Propane, heptachlorofluoro-, CFC-211 [a]	1		
Propane, hexabromofluoro- [a]	0.67		
Propane, hexachlorodifluoro-, CFC-212 [a]	1		
Propane, hexachlorofluoro-, HCFC-221 [a]	0.032		
Propane, monochlorodifluoro-, HCFC-262 [a]	0.0063		
Propane, monochlorofluoro-, HCFC-271 [a]	0.0055		
Propane, monochlorohexafluoro-, HCFC-226 [a]	0.045		
Propane, monochloropentafluoro-, HCFC-235 [a]	0.12		
Propane, monochlorotetrafluoro-, HCFC-244 [a]	0.035		
Propane, monochlorotrifluoro-, HCFC-253 [a]	0.0095		
Propane, pentabromodifluoro- [a]	0.62		
Propane, pentabromofluoro- [a]	0.44		
Propane, pentachlorodifluoro-, HCFC-222 [a]	0.03		
Propane, pentachlorofluoro-, HCFC-231 [a]	0.067		
Propane, pentachlorotrifluoro-, CFC-213 [a]	1		
Propane, tetrabromodifluoro- [a]	0.65		
Propane, tetrabromofluoro- [a]	0.39		
Propane, tetrabromotrifluoro- [a]	0.73		
Propane, tetrachlorodifluoro-, HCFC-232 [a]	0.028		
Propane, tetrachlorofluoro-, HCFC-241 [a]	0.019		
Propane, tetrachlorotetrafluoro-, CFC-214 [a]	1		
Propane, tetrachlorotrifluoro-, HCFC-223 [a]	0.028		
Propane, tribromofluoro- [a]	0.095		
Propane, tribromotetrafluoro- [a]	1		
Propane, trichlorodifluoro-, HCFC-242 [a]	0.025		
Propane, trichlorofluoro-, HCFC-251 [a]	0.0032		
Propane, trichloropentafluoro-, CFC-215 [a]	1		

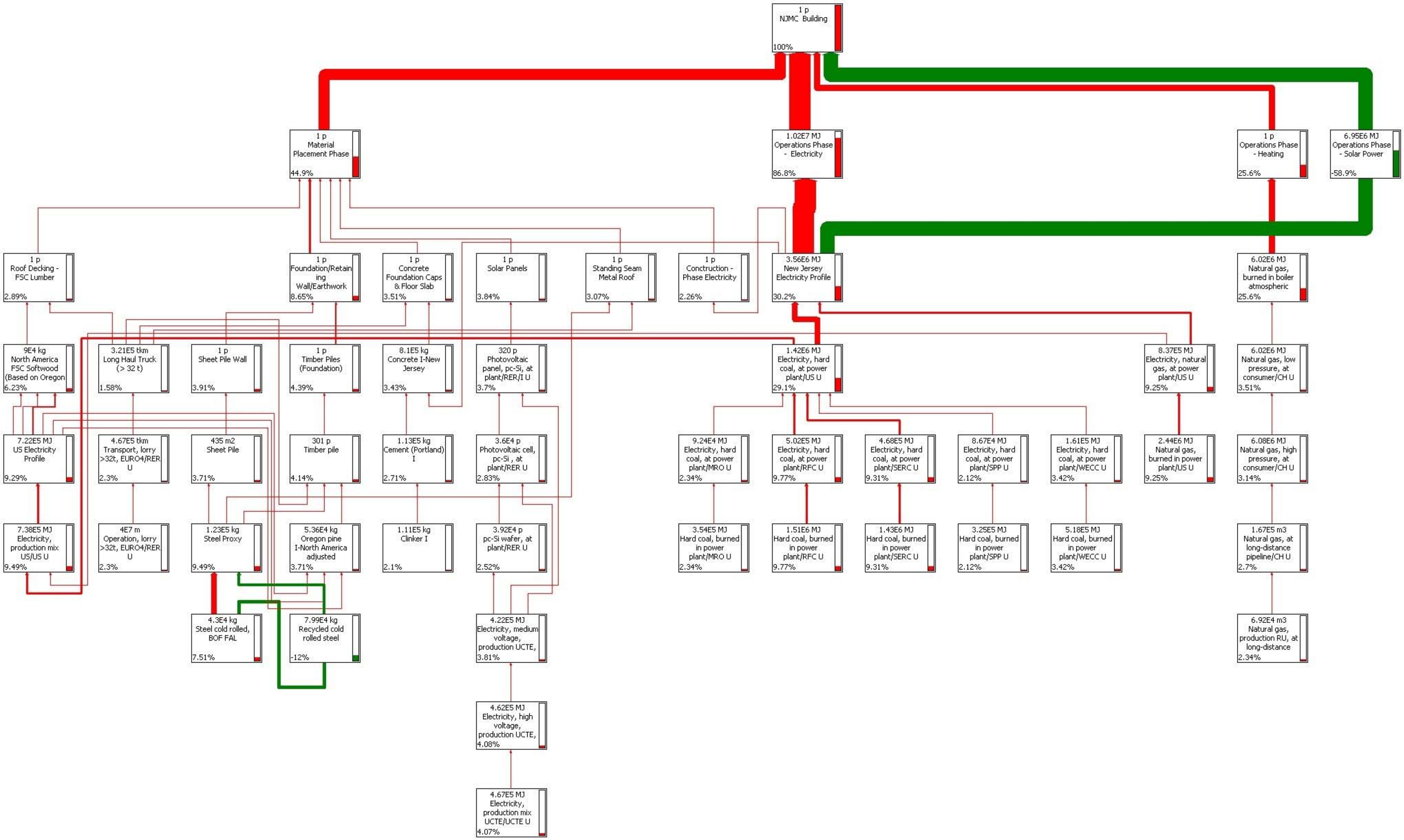
Environmental Impact Category Emission Factors for 2002+ (cont.)

Propane, trichlorotetrafluoro-, HCFC-224 [a]	0.03
Propane, trichlorotrifluoro-, HCFC-233 [a]	0.04

Note: (a) air emissions; (r) raw; (s) soil emissions; (w) water emissions.

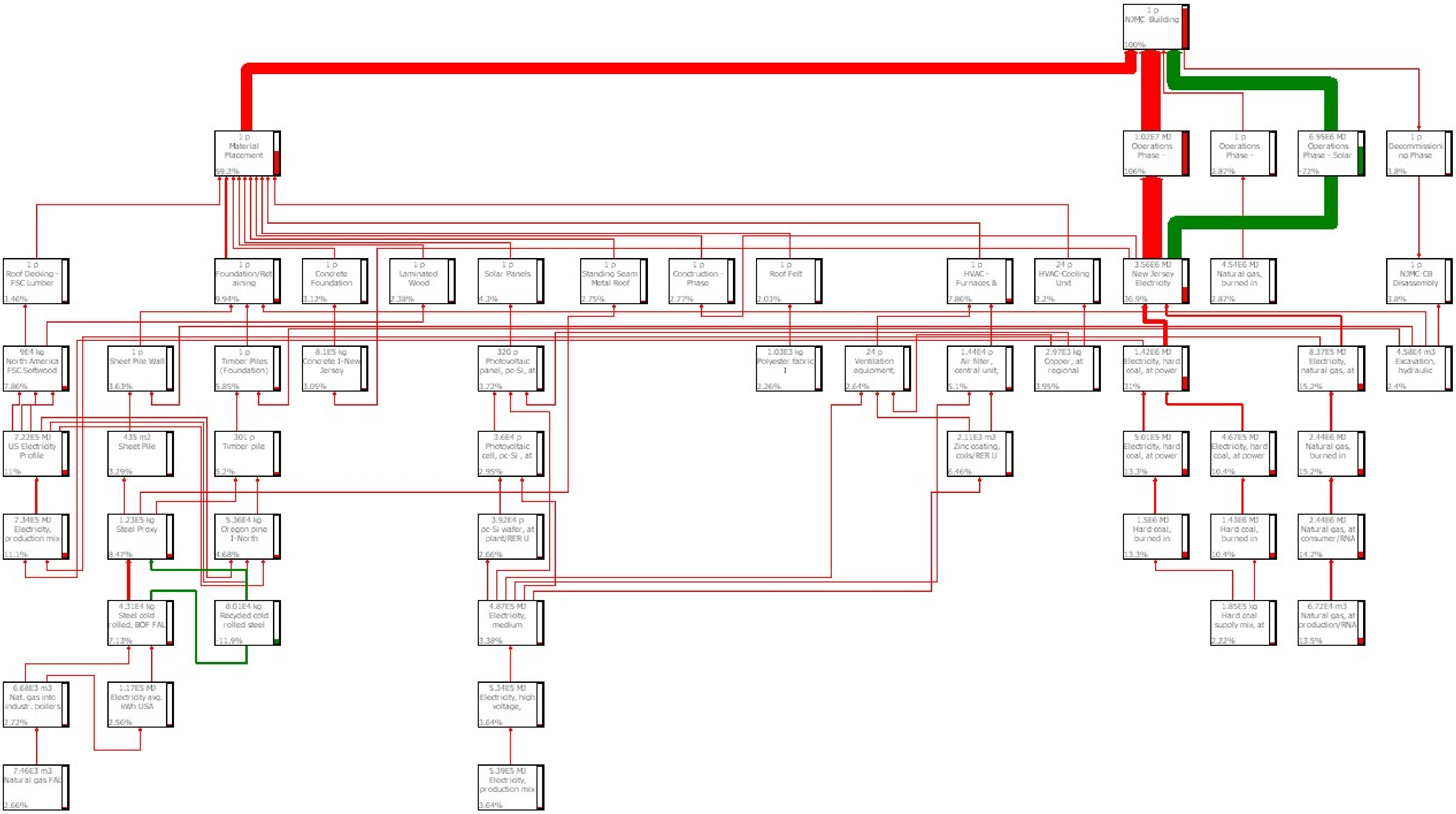
Appendix 2

Global Warming, Impact 2002+, 2% Cut-Off

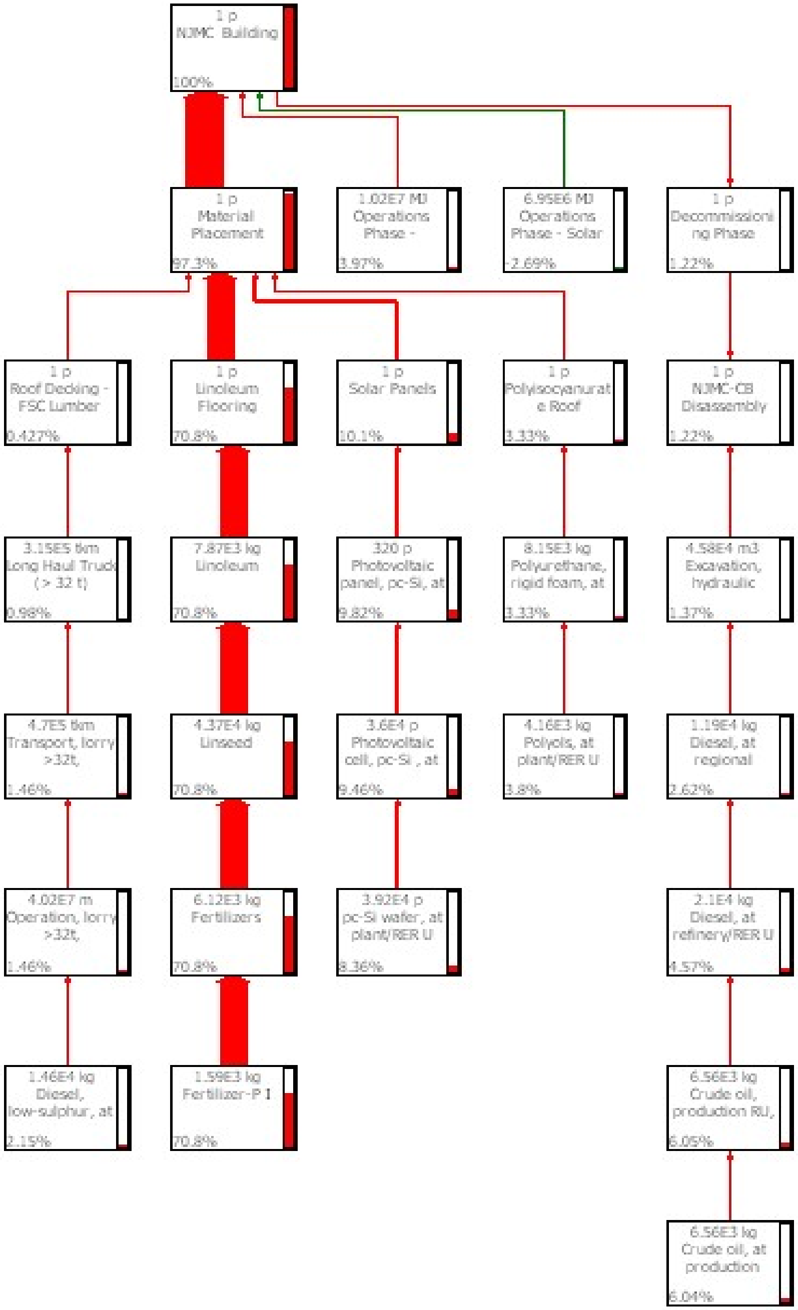


Appendix 2

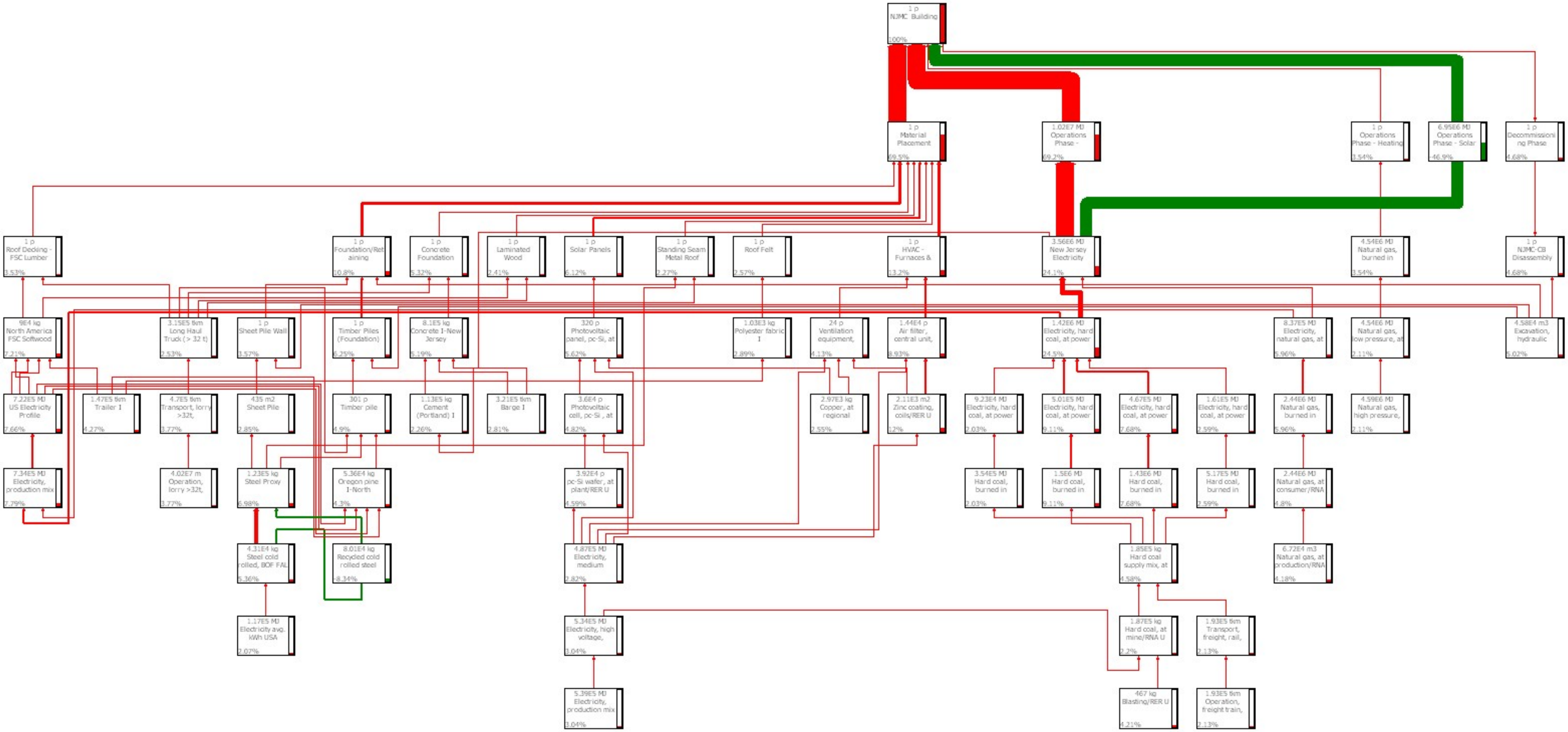
Aquatic Acidification, Impact 2002+, 2% Cut-Off



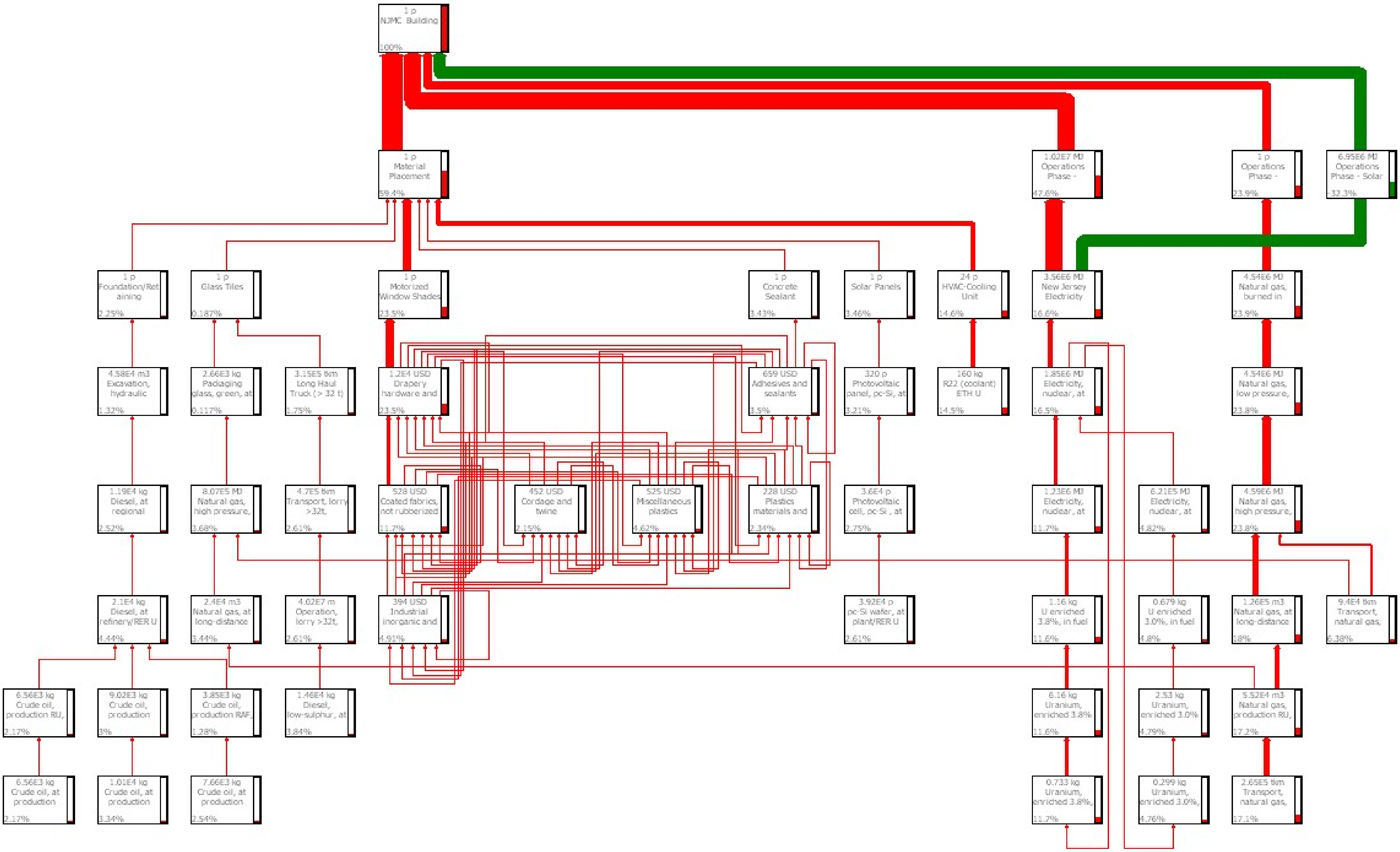
Aquatic Eutrophication, Impact 2002+ , 2% Cut-Off



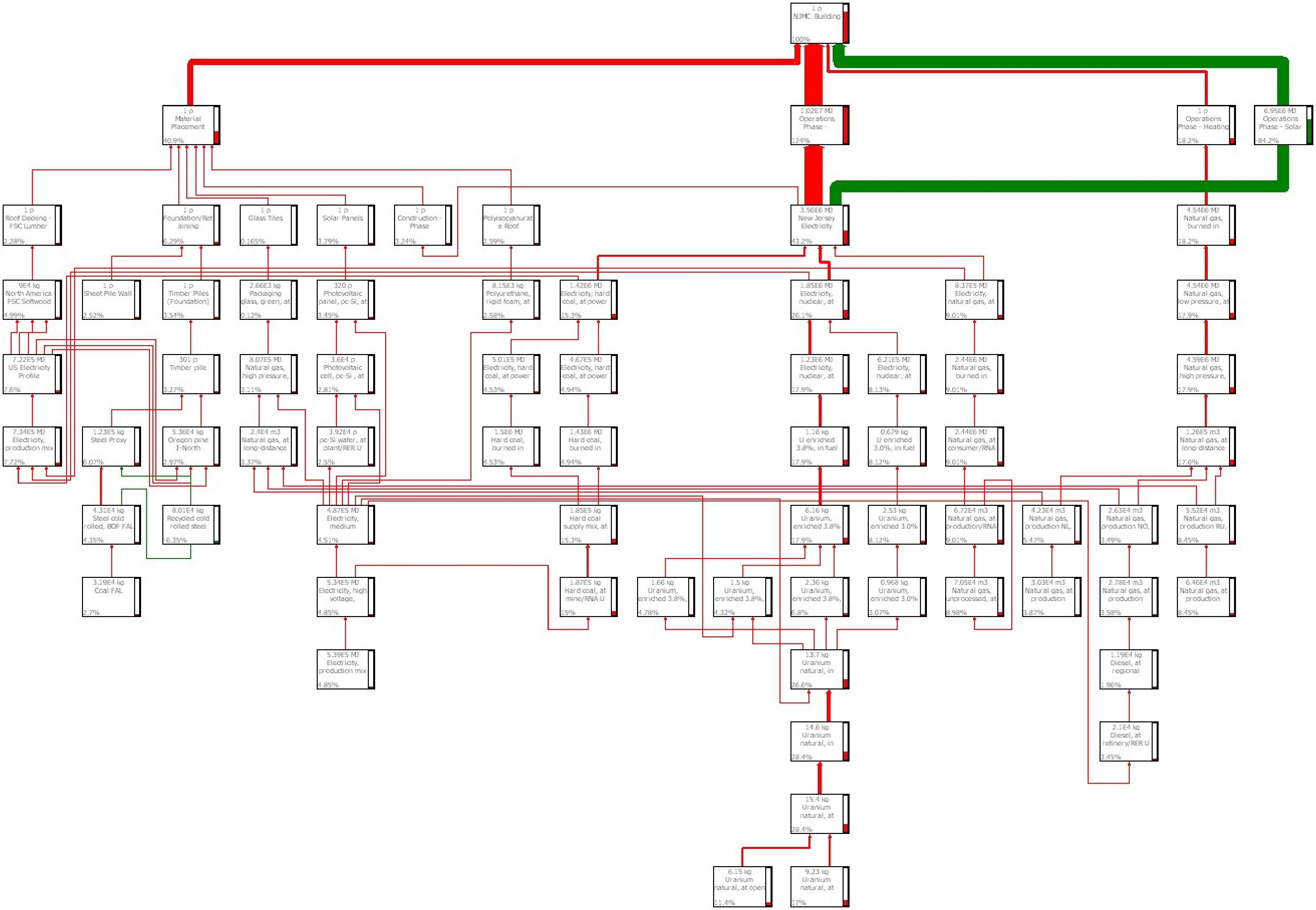
Terrestrial Acidification/Nutrification, Impact 2002+, 2% Cut-Off



Ozone Layer Depletion, Impact 2002+, 2% Cut-Off

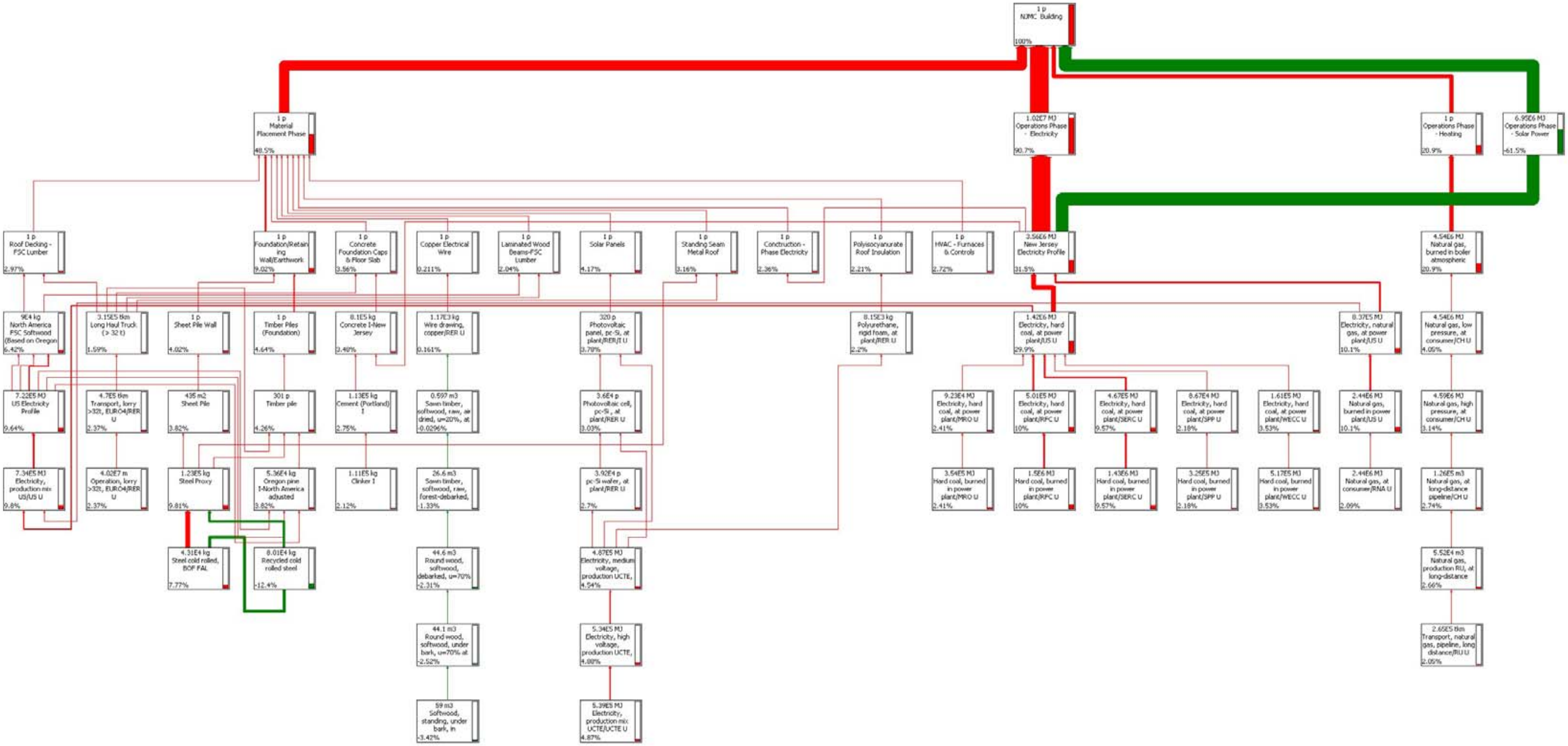


Non-Renewable Energy, Impact 2002+, 2% Cut-Off



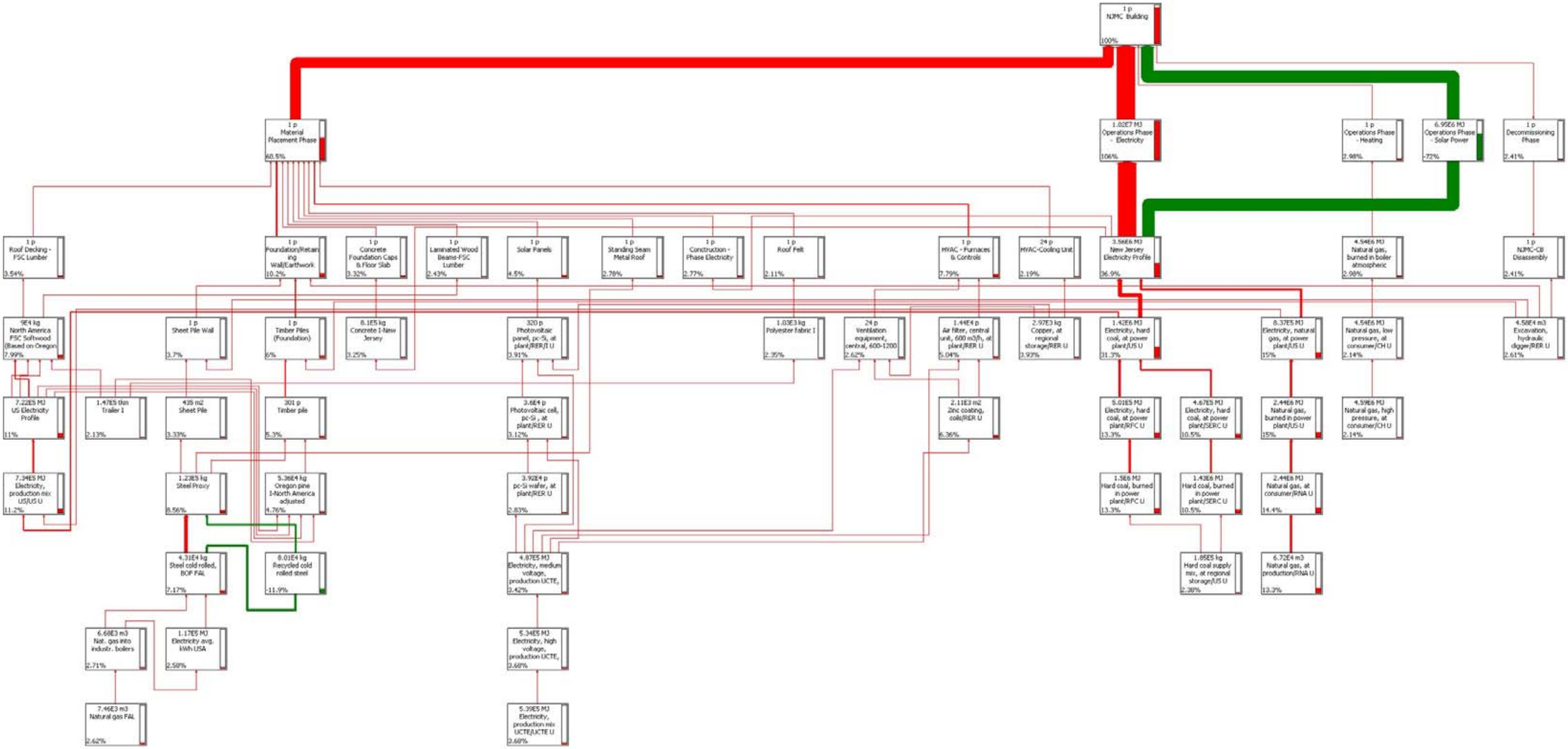
Appendix 2

Global Warming, BEES 4.0, 2% Cut-Off



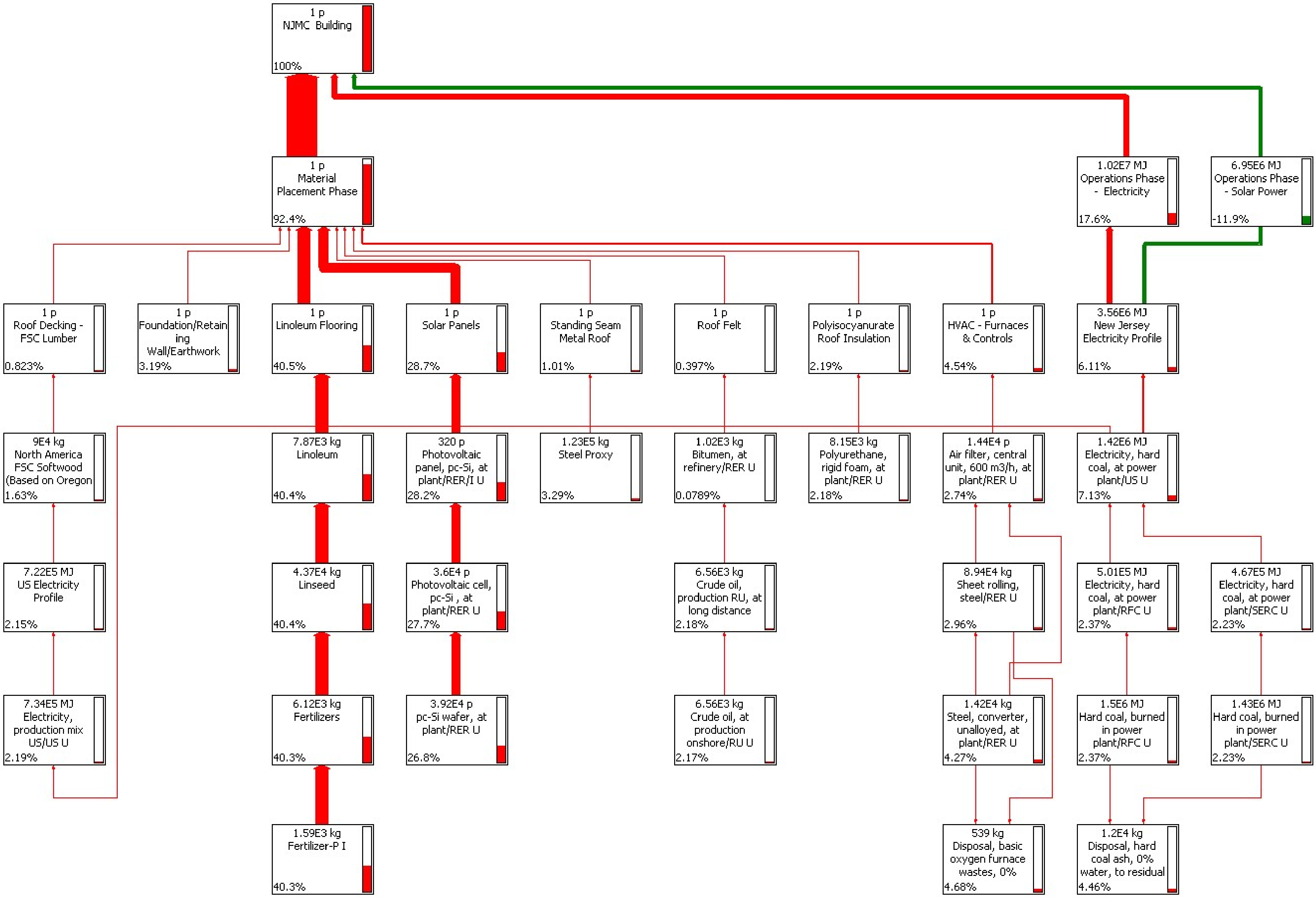
Appendix 2

Acidification, BEES 4.0, 2% Cut-Off



Eutrophication, BEES 4.0, 2% Cut-Off

Appendix
2



Appendix 2

Ozone Depletion, BEES 4.0, 3% Cut-Off