Life Cycle Primary Energy Use and Carbon Emission of Residential Buildings

Ambrose Dodoo

Sustainable Built Environment
Linnaeus University

26 January 2012
VÄXJÖ
Global primary energy supply

1 Mtoe = 0.042 EJ
Why buildings matter

- Buildings account for up to 40% of the global total primary energy use
Why buildings matter

- Buildings account for up to 40% of the global total primary energy use
- A third of the global total CO$_2$ emissions is linked to building energy use
Why buildings matter

• Buildings account for up to 40% of the global total primary energy use

• A third of the global total CO₂ emissions is linked to building energy use

• Improved material and energy efficiency in buildings is crucial for transition to sustainable energy future
  – Offer large potential to reduce CO₂ emissions to mitigate climate change
Studied building
4-storey building with 16 apartments and 1190 m² living area

Wood-frame building
Built in Växjö, Sweden, during the 1994 building code regime

Concrete-frame building
Hypothetical building with identical size and function
# Characteristics of buildings

<table>
<thead>
<tr>
<th>Description</th>
<th>Wood-frame building</th>
<th>Concrete-frame building</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Roof:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness mineral wool (cm)</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>U-value (W/m²K)</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>External walls:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness mineral wool (cm)</td>
<td>23.5</td>
<td>20.5</td>
</tr>
<tr>
<td>U-value (W/m²K)</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>Windows:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Double glazed</td>
<td>Double glazed</td>
</tr>
<tr>
<td>U-value (W/m²K)</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>External doors:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Double glazed</td>
<td>Double glazed</td>
</tr>
<tr>
<td>U-value (W/m²K)</td>
<td>1.19</td>
<td>1.19</td>
</tr>
<tr>
<td><strong>Foundation Floor:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded polystyrene (cm)</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>U-value (W/m²K)</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>Airtightness:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>l/(m²s) at 50 Pa</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Ventilation</strong></td>
<td>Mechanical, exhaust air</td>
<td>Mechanical, exhaust air</td>
</tr>
<tr>
<td><strong>Water taps</strong></td>
<td>Conventional</td>
<td>Conventional</td>
</tr>
</tbody>
</table>
Material mass of buildings

<table>
<thead>
<tr>
<th>Material</th>
<th>Wood frame</th>
<th>Concrete frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macadam</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Concrete</td>
<td>10000</td>
<td>100000</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>1000</td>
<td>10000</td>
</tr>
<tr>
<td>Lumber</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Mortar</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Plywood</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Insulation</td>
<td>1000</td>
<td>10000</td>
</tr>
<tr>
<td>Particleboard</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Iron/steel</td>
<td>1000</td>
<td>10000</td>
</tr>
<tr>
<td>Glass</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Putty/fillers</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Blocks</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Appliances</td>
<td>1000</td>
<td>10000</td>
</tr>
<tr>
<td>Paper</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Plastic (PVC)</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Ceramic tiles</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Paint</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Porcelain</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Copper</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Zinc</td>
<td>100</td>
<td>1000</td>
</tr>
</tbody>
</table>
Modeled activities and flows

**Production / Retrofitting phases**
- Extraction, processing and transport of materials
- Energy recovery from biomass residues
- On-site construction work

**Operation phase**
- Space heating
- Electricity for ventilation
- Tap water heating
- Electricity for household and facility management

**End-of-life phase**
- Demolition
- Energy recovery from wood
- Recycling of concrete and steel to replace virgin raw material

**Energy supply system**
- Coal-based electricity for material production
- Bioenergy replace coal
- Full energy chain accounting, including conversion / fuel cycle losses

- Resistance heating, or heat pump, or district heating
- District heating produced with a biomass-fired CHP plant
- Electricity produced with a biomass-fired condensing plant
- Full energy chain accounting, including conversion / fuel cycle losses

- Bioenergy replace coal
- Full energy chain accounting, including conversion / fuel cycle losses
Modeled activities and flows

**Production / Retrofitting phases**
- Extraction, processing and transport of materials
- Energy recovery from biomass residues
- On-site construction work

**Operation phase**
- Space heating
- Electricity for ventilation
- Tap water heating
- Electricity for household and facility management

**End-of-life phase**
- Demolition
- Energy recovery from wood
- Recycling of concrete and steel to replace virgin raw material

**Energy supply system**
- Coal-based electricity for material production
- Bioenergy replace coal
- Full energy chain accounting, including conversion / fuel cycle losses

**Energy supply system**
- Resistance heating, or heat pump, or district heating
- District heating produced with a biomass-fired CHP plant
- Electricity produced with a biomass-fired condensing plant
- Full energy chain accounting, including conversion / fuel cycle losses

**Energy supply system**
- Bioenergy replace coal
- Full energy chain accounting, including conversion / fuel cycle losses
Material flows from natural resources to building

- Ore
- Forest
- Extraction
- Processing
- Construction
- Building
- Energy supply
- Biomass residues

Material flow
Fuel-/energy flow
Flow of biomass residues in building’s production

Forest residue → Harvested roundwood → Processing residue → Wood-based building materials → Construction residue
Modeled activities and flows

**Production / Retrofitting phases**
- Extraction, processing and transport of materials
- Energy recovery from biomass residues
- On-site construction work

**Operation phase**
- Space heating
- Electricity for ventilation
- Tap water heating
- Electricity for household and facility management

**End-of-life phase**
- Demolition
- Energy recovery from wood
- Recycling of concrete and steel to replace virgin raw material

**Energy supply system**
- Coal-based electricity for material production
- Bioenergy replace coal
- Full energy chain accounting, including conversion / fuel cycle losses

**Energy supply system**
- Resistance heating, or heat pump, or district heating
- District heating produced with a biomass-fired CHP plant
- Electricity produced with a biomass-fired condensing plant
- Full energy chain accounting, including conversion / fuel cycle losses

**Energy supply system**
- Bioenergy replace coal
- Full energy chain accounting, including conversion / fuel cycle losses
System perspective on energy supply and demand

District heating system:
- Natural resource
  - Fuel chain
    - Heat and power generation
      - Electricity
      - Heat
      - End-use heating system
      - Heat
      - Demand

Electric heating system:
- Natural resource
  - Fuel chain
    - Power generation
      - Electricity
      - End-use heating system
      - Heat
      - Demand

Boundaries:
- Large-scale electricity and heat supply
- Supply system
- System boundaries
Modeled activities and flows

**Production / Retrofitting phases**
- Extraction, processing and transport of materials
- Energy recovery from biomass residues
- On-site construction work

**Operation phase**
- Space heating
- Electricity for ventilation
- Tap water heating
- Electricity for household and facility management

**End-of-life phase**
- Demolition
- Energy recovery from wood
- Recycling of concrete and steel to replace virgin raw material

**Energy supply system**
- Coal-based electricity for material production
- Bioenergy replace coal
- Full energy chain accounting, including conversion / fuel cycle losses

**Energy supply system**
- Resistance heating, or heat pump, or district heating
- District heating produced with a biomass-fired CHP plant
- Electricity produced with a biomass-fired condensing plant
- Full energy chain accounting, including conversion / fuel cycle losses

**Energy supply system**
- Bioenergy replace coal
- Full energy chain accounting, including conversion / fuel cycle losses
End-of-life building materials

- Demolition
- Wood residues
- Concrete waste
- Iron / steel scrap
Production primary energy balance of buildings

-400 -200 0 200 400 600 800

Concrete frame
Wood frame

Primary energy use (kWh/m²)

Material production
On-site construction
Biomass residue recovery
Total
Annual profile of final space heat demand of buildings in different climatic locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Relative location</th>
<th>Average temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Växjö</td>
<td>South</td>
<td>6.5 °C</td>
</tr>
<tr>
<td>Östersund</td>
<td>Middle</td>
<td>2.5 °C</td>
</tr>
<tr>
<td>Kiruna</td>
<td>North</td>
<td>-1.2 °C</td>
</tr>
</tbody>
</table>

The graph shows the annual profile of final space heat demand for buildings with wood and concrete frames in different climatic locations:

- **Wood frame (Kiruna)**
- **Concrete frame (Kiruna)**
- **Wood frame (Östersund)**
- **Concrete frame (Östersund)**
- **Wood frame (Växjö)**
- **Concrete frame (Växjö)**

The x-axis represents the day of the year, while the y-axis shows the building heat demand in kW.
Annual profile of final space heat demand of buildings built to different standards and located in Växjö
Annual primary energy use for space heating of buildings with different heating systems in Växjö

Supply system: Biomass-based steam turbine
Annual operation primary energy use of buildings with different heating systems located in Växjö

![Chart showing primary energy use for different heating systems and building materials.](chart.png)

- **Concrete frame**
  - Household electricity
  - Tap water heating
  - Ventilation electricity
  - Space heating

- **Wood frame**
  - Household electricity
  - Tap water heating
  - Ventilation electricity
  - Space heating

- **Concrete frame**
  - Household electricity
  - Tap water heating
  - Ventilation electricity
  - Space heating

- **Wood frame**
  - Household electricity
  - Tap water heating
  - Ventilation electricity
  - Space heating

- **Electric resistance heating**
  - Household electricity
  - Tap water heating
  - Ventilation electricity
  - Space heating

- **Heat pump**
  - Household electricity
  - Tap water heating
  - Ventilation electricity
  - Space heating

- **District heating**
  - Household electricity
  - Tap water heating
  - Ventilation electricity
  - Space heating

**Supply system**: Biomass-based steam turbine
End-of-life primary energy balance of buildings

Primary energy use (kWh/m²)

- Demolition
- Concrete recycling
- Steel recycling
- Wood recovery for biofuel
- Total

Concrete frame
Wood frame
Life cycle primary energy use of district heated buildings in Växjö for a 50-year lifespan

Supply system: Biomass-based steam turbine

<table>
<thead>
<tr>
<th>Primary energy (kWh/m²)</th>
<th>Concrete frame</th>
<th>Wood frame</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total used</td>
<td>11253</td>
<td>11042</td>
<td>211</td>
</tr>
<tr>
<td>Benefits from production and end-of-life</td>
<td>-537</td>
<td>-713</td>
<td>176</td>
</tr>
<tr>
<td>Balance</td>
<td>10716</td>
<td>10329</td>
<td>387</td>
</tr>
</tbody>
</table>

- Demolition
- Household electricity
- Tap water heating
- Ventilation electricity
- Space heating
- On-site construction
- Material production
- Concrete recycling
- Steel recycling
- Wood recovery for bioenergy

Concrete recycling
Wood recovery for bioenergy
Carbon flows due to cement reactions for buildings

Calcination

Concrete frame: Emission due to calcination (tC)

Wood frame: Uptake due to carbonation (tC)

Carbonation

Concrete-frame: Uptake due to carbonation (tC)

Wood-frame: Uptake due to carbonation (tC)
Net carbon emissions of buildings at year of construction

- Material production
- Net cement reactions
- Biomass fossil fuel replacement
- Forest carbon stock change
- Building carbon stock change
- Total

Concrete frame vs. Wood frame
Net carbon emissions of buildings over life cycle of buildings

Material production
Net cement reactions
Biomass fossil fuel replacement
Forest carbon stock change
Building carbon stock change
Recycled concrete and steel benefits
Total

Concrete frame
Wood frame
Impacts of building energy-efficiency standards

Annual final energy use for operation

Supply system: Biomass-based steam turbine
Impacts of building energy-efficiency standards

Annual final and primary energy use for operation

Supply system: Biomass-based steam turbine
Impacts of building energy-efficiency standards

Space heating and production primary energy

Relative distribution of primary energy

Electric heated building

District heated building
Impacts of building energy-efficiency standards

Life cycle primary energy implications

(Assumed building lifespan of 50 years)

Supply system: Biomass-based steam turbine
## Impacts of energy efficiency retrofit measures

### Annual final operation energy, before and after retrofit measures are applied

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Retrofit measure</th>
<th>Annual final operation energy use (kWh/m² year)</th>
<th>Space heating</th>
<th>Tap water heating</th>
<th>Ventilation electricity</th>
<th>Household /facility electricity</th>
<th>Total</th>
<th>Cumulative change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>–</td>
<td>166</td>
<td>70</td>
<td>40</td>
<td>4</td>
<td>52</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Taps</td>
<td>Efficient hot water taps</td>
<td>150</td>
<td>70</td>
<td>24</td>
<td>4</td>
<td>52</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>Roof</td>
<td>U-value from 0.13 to 0.08</td>
<td>149</td>
<td>69</td>
<td>24</td>
<td>4</td>
<td>52</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Windows</td>
<td>U-value from 1.9 to 0.90</td>
<td>131</td>
<td>51</td>
<td>24</td>
<td>4</td>
<td>52</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Doors</td>
<td>U-value from 1.19 to 0.90</td>
<td>131</td>
<td>51</td>
<td>24</td>
<td>4</td>
<td>52</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>External walls</td>
<td>U-value from 0.20 to 0.10</td>
<td>123</td>
<td>43</td>
<td>24</td>
<td>4</td>
<td>52</td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>Ventilation</td>
<td>Heat recovery, η = 85%</td>
<td>97</td>
<td>13</td>
<td>24</td>
<td>8</td>
<td>52</td>
<td></td>
<td>69</td>
</tr>
</tbody>
</table>

U-values in W/m²K
Impacts of energy efficiency retrofit measures

Annual primary energy use for (space and tap water) heating and ventilation

Supply system: Biomass-based steam turbine
Impacts of energy efficiency retrofit measures

Primary energy use in complete life cycle of buildings
(Assumed lifespan of 50 years)

Supply system: Biomass-based steam turbine
Impacts of ventilation heat recovery (VHR) systems

Change in annual primary energy use for space heating and ventilation

Supply system: Biomass-based steam turbine (BST) or Biomass-based integrated gasification with combined cycle (BIGCC)
Impacts of ventilation heat recovery (VHR) systems

Net annual primary energy savings

Supply system: Biomass-based steam turbine (BST) or Biomass-based integrated gasification with combined cycle (BIGCC)

Net primary energy savings (kWh/m²)

- Conventional
- Passive

Electric resistance heating
Heat pump
District heating, 50% CHP
District heating, 90% CHP
Impacts of ventilation heat recovery (VHR) systems
More optimally designed CHP production systems

Supply system: Biomass-based steam turbine (BST) or Biomass-based integrated gasification with combined cycle (BIGCC)
Conclusions

• Energy savings due to thermal mass is small for a Nordic building
  – Varies with the climatic location, and
  – Energy efficiency level of building
Conclusions

• Energy savings due to thermal mass is small and varies with the climate and energy efficiency levels of buildings

• Concrete building has slightly lower space heating demand than wood alternative
  – Higher thermal mass of concrete-based material
Conclusions

• Energy savings due to thermal mass is small and varies with the climate and energy efficiency levels of buildings
• Concrete building has slightly lower space heating demand than wood alternative
• Still, wood building has lower primary energy balance than concrete alternative
  – Less energy needed for material production
  – More energy available from biomass residues
Conclusions

• Energy savings due to thermal mass is small and varies with the climate and energy efficiency levels of buildings
• Concrete building has slightly lower space heating demand than wood alternative
• Still, wood building has lower primary energy balance than concrete alternative
• Wood building has lower carbon balance than concrete alternative, even if post-use carbonation is accounted
  – Less fossil fuel emission for material production
  – Less cement process emission
  – More fossil fuel substitution by biomass residues
  – Effect of carbonation of post-use concrete material is small, overall
Conclusions

- Energy savings due to thermal mass is small and varies with the climate and energy efficiency levels of buildings.
- Concrete building has slightly lower space heating demand than wood alternative.
- Still, wood building has lower primary energy balance than concrete alternative.
- Wood building has lower carbon balance than concrete alternative, even if post-use carbonation is accounted.
- System-wide and life cycle perspectives are required to evaluate implications of energy standards and measures.
  - Full energy chains, from natural resources to final energy service.
  - Energy demand and supply sides, and their interaction.
Conclusions

• Energy savings due to thermal mass is small and varies with the climate and energy efficiency levels of buildings
• Concrete building has slightly lower space heating demand than wood alternative
• Still, wood building has lower primary energy balance than concrete alternative
• Wood building has lower carbon balance than concrete alternative, even if post-use carbonation is accounted
• System-wide and life cycle perspectives are required to evaluate implications of energy standards and measures
• Wood-frame passive house with cogeneration-based district heating gives low life cycle primary energy use
Thank you for your attention
Conclusions (II)

- The importance of the other life cycle phases increase as buildings are built to improved levels of energy efficiency.
- Material choice matters and becomes more important as buildings are built to improved levels of energy efficiency.
- Electric heated passive house does not achieve lower primary energy use than district heated conventional house.