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An Empirical Study on Life Cycle Assessment of Double-Glazed Aluminium-Clad Timber Windows

ABSTRACT

Purpose:
Life cycle assessment (LCA) is a useful tool to determine the environmental performance of materials and products. This work aims to undertake LCA of double-glazed aluminium-clad timber windows in order to determine their environmental performance.
Methodology:
The scope of the LCA study covers the production and the use of windows over a 30-year life span. The LCA exercise has been carried out by auditing the materials and processes involved in the making of the windows. Windows production facilities were visited to investigate the respective quantities and embodied energy of the major constituting materials i.e. timber, aluminium, glass, infill gases and auxiliary components. Main processes involved i.e. powder coating of aluminium cladding profiles, glazing unit production and window assembly were also examined. SimaPro software was used to calculate the environmental impacts associated with the windows for three types of glazing infills: Argon (Ar), Krypton (Kr) and Xenon (Xe).
Findings:
Embodied energy of a standard sized (1.2m x 1.2m) double glazed aluminium-clad timber window is found to be 899 MJ, 1,402 MJ, and 5,400 MJ for Argon (Ar), Krypton (Kr) and Xenon (Xe) infill gases, respectively. It is also found that an Argon-filled window can lose 95,130 kWh of energy resulting into over 37,000 kg of CO_2 emissions.
Originality/Value:
Besides carrying value for research community, the findings of this study can help the building and construction industry adopt windows that are energy efficient and environmentally less burdensome. It can also help the concerned legislative bodied.

Keywords:

Buildings, sustainability, life cycle assessment, windows, timber, aluminium

1. INTRODUCTION

With the start of the twenty first century global has presented itself as one of the greatest challenges mankind is facing. The growing levels of greenhouse gases (GHG) in the atmosphere are reported to have increased the global average temperature by 0.5°C over the last century (Asif, 2011). In the absence of a global effort the atmospheric temperature is projected to further increase by up to 6°C by the end of this century (Ghosh, 2012). Melting glaciers are leading to sea level rise. The annual ice loss in Antarctica as a result of global warming has been reported to be nearly 160 billion tonnes (McMillan et al., 2014). Global warming is also leading to seasonal disorder, food crisis and a pattern of more frequent and intense weather related events including floods, storms, heat waves, forest fires and droughts. Estimates suggest that since 1900 the natural disasters including floods, storms, earthquakes, bushfires have resulted into 8 Million deaths and over 7 Trillion$ of economic loss (KIT, 2016) (Amos, 2016). It has been reported that by 2060 over one billion people around the world would be living in cities with risk of calamitous flooding as a consequence of climate change (BBC, 2016). While 2016 is on course to be the warmest year since records began, 195 countries, through the Paris Agreement, have committed themselves to the world's first-ever legally binding deal to tackle climate change by limiting global warming under 2°C (Matt, 2016; EC, 2016).

Buildings have an important role in the global energy and environmental scenario as they are responsible for over 40 % of world's total energy consumption and more than a third of GHG emissions (UNEP, 2009; Asif, 2016; Asif et al., 2017; Alrashed and Asif, 2015). A building consumes energy through its entire life i.e. from construction to demolition. The use of energy in buildings during their life cycle is in both direct and indirect form. The direct use of energy is for construction, operation, maintenance, renovation, and decommissioning; while the indirect use of energy is attributed to the production of material employed in its construction and equipment (Cabeza et al., 2014) (Sartori and Hestnes, 2007). The rate of annual growth of carbon dioxide emissions since 1970s has been 2.5% and 1.7% for commercial and residential buildings respectively (Seppo, 2004; Adalberth et al., 2001). Buildings are also responsible for emissions of significant non-CO_2 based greenhouse gases (GHGs) such as halocarbons, Chlorofluorocarbons (CFCs), and hydrofluorocarbons (HFCs). It is also estimated that, in a business as usual scenario, GHG emissions from buildings are likely to be more than twice over the next two decades. If the targets for reduction in GHG emissions are to be achieved, the building sector needs to play an important role. It is vital that, while adding to the overall stock of buildings, the impacts on climate change during the entire life cycle of buildings are mitigated. The building sector is understood to have the greatest potential of reducing environmental emissions in comparison to other sectors i.e. transportation and industry. With the commercially available and proven technologies, energy consumption in new as well as existing buildings can be curtailed by 30% to 80 % while achieving a net profit within their lifespan (UNEP, 2009).

Windows are important structural elements which due to their multi-purpose role greatly influence the energy and environmental performance of a building. Estimates for example suggest that windows account for 6% of the total energy consumed in UK's residential sector (Weir and Muneer, 1998). From the sustainability perspective, environmental performance of windows is an important aspect to be considered. Environmental performance of windows is determined by the energy consumed during their production as well as usage phase, associated depletion of natural resources and end-of-life disposal impacts (Edwards and Schelling, 1996). Windows have been found to be capable of over 75% saving in energy consumption and environmental emissions as a result of improved glazing unit (Asif et al., 2005; Asif and Muneer 2013). Environmental impacts directly associated with the production of windows are related to extraction of the involved materials (main frame and sash constituent materials i.e. wood, steel, aluminium, PVC and glass as well as support materials such as plastics, rubber, chemicals and coatings), refinement of materials and window manufacturing/assembly process (EC, 2010).

Windows made from ecologically better materials and with superior energy performance, can significantly help towards sustainability of buildings. Windows come in a wide range of frame materials and glazing compositions. Timber, having a long history as a building material, has been traditionally used to manufacture windows. In modern times, a range of alternative materials i.e. aluminium, steel, polyvinyl chloride (PVC) and composite materials have been introduced in the window market (Asif et al., 2005). These materials also come with claddings of aluminium and PVC. Being an effective member of window family, aluminium-clad timber windows are important to be evaluated in terms of their ecological impacts. Life cycle assessment (LCA) is a very useful tool to determine environmental impacts of the materials and processes employed in the production of windows (Weir and Muneer, 1998). LCA has been widely used to evaluate environmental impacts of different types of buildings and materials (Le et al., 2018; Kayan, 2017).

This presented study aims to undertake an energy and environmental impact assessment - the core of any LCA study - for double glazed aluminium-clad timber windows. Its key objectives are to:

- Undertake audit of materials consumed in producing double glazed windows using Ar, Kr and Xe infill gases

- Quantify the embodied energy of these windows
- Calculate the environmental impacts of the windows during the production phase
- Compare their energy and environmental performance during the operational phase

The study employed empirical data that was collected from the windows manufacturing facility. Windows production units were visited to examine the processes involved and to gather the concerned data on the materials, energy content. Empirical data was gathered by visiting the windows production facilities. Audit reports and records were also examined besides conducting interviews of concerned personnel and using SimaPro modeling tool to calculate the environmental emissions.

2. LIFE CYCLE ASSESSMENT AND METHODOLOGY OF THE STUDY

All building materials and products have a certain degree of environmental impacts. A typical building product can have environmental impacts attributed to various stages of their production and utilization as highlighted in Figure 1. Certain material can have profound impacts with diverse implications (Elshafei and Negm 2015; Asif et al 2002). It is therefore important to timely estimate such impacts. Life cycle assessment (LCA) is an important technique in this respect. Life cycle assessment is defined as: ‘A process to evaluate the environmental burdens associated with a product, system, or activity by identifying and quantitatively or qualitatively describing the energy and materials used, and wastes released to the environment, and to assess the impacts of the energy. The assessment includes the entire life cycle of the product or activity, encompassing, extracting and processing the raw materials; manufacturing; distribution; use; reuse; maintenance; recycling and final disposal; and all transportation involved’(Edwards and Schelling, 1996).

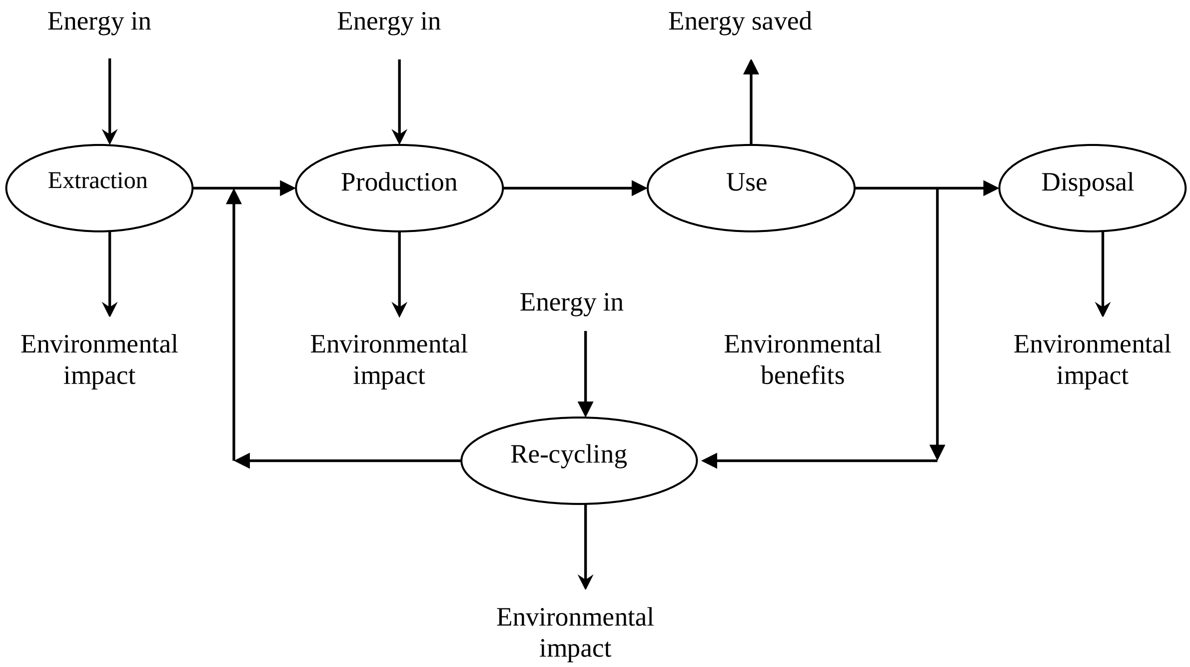


Figure 1: Typical life cycle of building products

LCA works through a systemic approach towards evaluating environmental impacts. For its comprehensive approach and effective results, it has attracted significant interest around the globe (Asdrubali et al., 2013; Buyle et al., 2013). According to the European Union (EU), LCA is one of the most innovative approaches to determine the environmental performance of products during their life cycle (EC, 2010). Generally, a LCA study encompasses four interwoven stages: firstly planning, secondly inventory determination, thirdly impact analysis and lastly improvement assessment. Findings of a LCA are influenced by its planning phase that signifies its objectives and scope. Results are also heavily dependent upon the involved inventory analysis.

The LCA approach has been extensively used by researchers to determine the energy and environmental performance of windows. LCA studies have varied in their scope in terms of types of materials and life cycle stages (Salazar, 2014). Among the earlier studies in this respect is the LCA of multi-glazed timber window carried out by Weir and Muneer (Weir and Muneer, 1998). ENTEC compared the environmental impacts of PVC and timber windows (ENTECT, 2000). Asif et al compared different types of window frame materials from sustainability perspective (Asif et al 2002). Salazar and Sowlati also carried out LCA study on different types of frame materials (Salazar and Sowlati, 2008). In terms of life cycle stages, LCA studies can be broadly classified into four categories: production phase; production and use phase; production, use and repair phase; and production, use, and landfilling/recycling phase (Weir and Muneer, 1998; Kiani et al 2004; Blom, 2010; Salazr, 2014). LCA studies on multi-glazed windows have mainly dealt with air and Argon based glazing systems (Salazr, 2014; Switala-Elmhurst, 2014)). The present study has investigated Ar, Kr and Xe based double glazed windows.

The LCA methodology adopted in the present study, as shown in Figure 2, has been based upon the four-phase approach as widely suggested in literature including the ISO 14040 series (ISO, 1997; Heravi et al 2016). The stages involved in the life cycle of aluminium-clad timber windows is shown in Figure 3, which also explains production/extraction of raw materials and processing involved at various stages. The scope of the present study in terms of its boundaries has been highlighted as the shaded area. The study covers the production and operational phase of double glazed aluminium-clad timber windows. It calculates their embodied energy for three types of infill gases: Ar, Kr and Xe. It incorporates a detailed audit of the total energy consumption in production of these windows, that is, the energy involved in extraction/production of window parts and in processes involved in window manufacturing. Environmental burdens associated with the involved materials and production processes have also been figured out with the help of SimaPro software. The operational phase of windows has been investigated, for a period of 30 years, in terms of heat loss through them and the consequent CO_2 emissions. Under the inventory analysis, materials involved in the production of windows were identified. In this respect empirical data collection was carried out by visiting different window manufacturing facilities situated in Norway. Three different facilities were visited including wood treatment unit, alumninium coating unit and the main window production unit that housed facilities for manufacturing/profiling of different window components as well as their assembly into a complete window unit and packaging. Data was collected by observing processes at the facilities, studying records and annual audit reports (i.e. energy rating and operational hours of equipment, specifications of materials and chemicals/coatings, quantification of production, operational schedule of facilities, utility bills) taking sample readings and measurements, and interviewing staff. Given the nature of the study, unstructured interview were held with the concerned staff on shop floors and in administration offices of these facilities to substantiate the gathered information by having further queries answered about the production processes and the data records. This exercise led to development of material inventory. Subsequently SimaPro software was used to calculate the environmental emissions associated with the materials consumed in the production of the studied windows. The operational energy associated with windows has been calculated as the energy loss through it with the help of standard American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) equation.

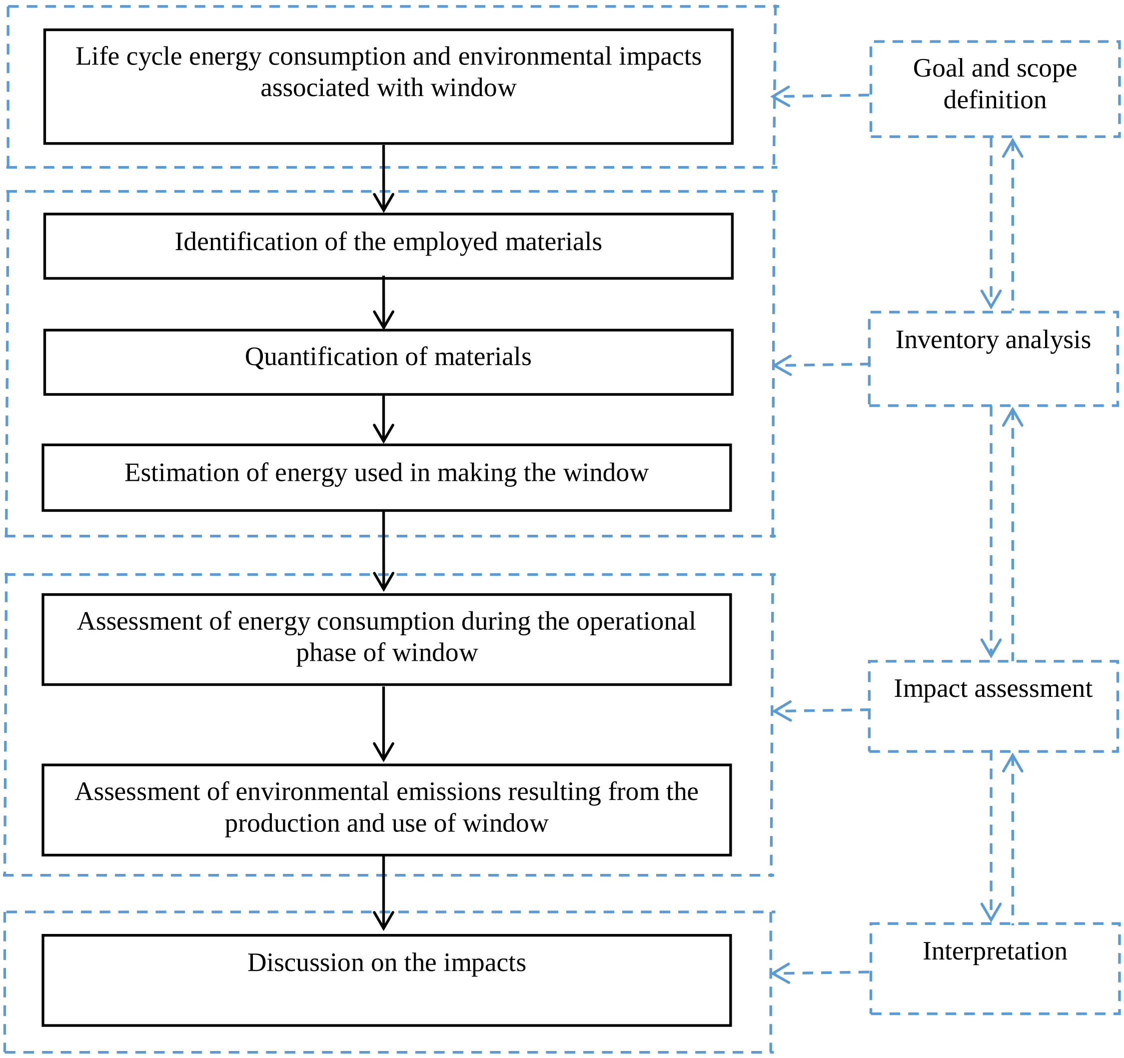


Figure 2: Methodology of the window LCA study

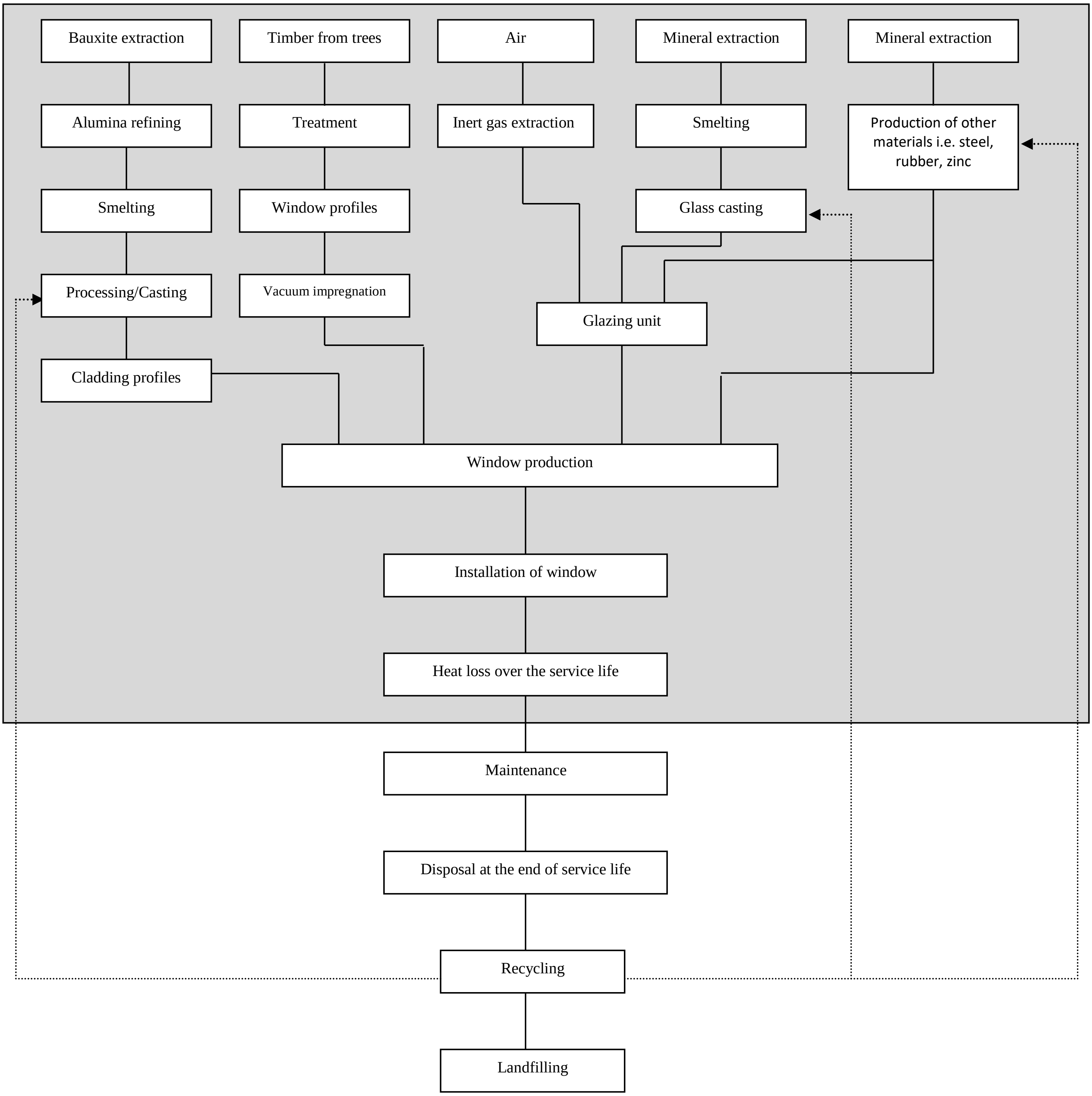


Figure 3: Cradle to grave overview of windows

3. MATERIAL AND EMBODIED ENERGY AUDIT

3.1. Aluminium cladding

Aluminium cladding of windows means applying aluminium profiles on the exterior surface of their frame and sash for improved protection from weathering effects. In cladding, a sheet of aluminium (about 3 mm in thickness) is attached on the exterior surface of the window frame, with a gap of about 6 mm being maintained between the cladding and timber surface to allow for optimum drainage and drying of the wood after, for example, rain and snow. It keeps the wood underneath protected from environmental degradation factors and helps increasing the overall service life of the window. Cladding has an aesthetic aspect as well, since it is available in a wide range of colours providing a cosmetic touch to the exterior of windows. Another important role of cladding is its economic contribution by cutting down the maintenance cost of the windows. The embodied energy of aluminium cladding is broadly divided into three areas: energy content of the used aluminium metal, energy used for powder coating the aluminium profiles and the energy used for profile cutting.

3.1.1. Aluminium Profiles

Aluminium is an abundantly found element in nature as over 8% of the earth's crust is made of it (Haupin, 1987). It, however, does not exist free and exists in combination with elements like silicon, iron and oxygen in the form of rock or clay termed as bauxite. Pure aluminium is a silvery-white, soft, ductile and corrosion-resistant metal. By alloying with other metals a range of materials is produced which, by retaining the common characteristics of lightness and durability, give considerable increase in tensile strength and hardness. Due to its leading characteristics - high strength to weight ratio, excellent mechanical and physical properties - aluminium has emerged as one of the most widely used materials in the building sector. The energy content of aluminium, as reported by different research findings varies. This variation might be because of the differences of the respective frameworks i.e. nature and boundaries of the investigations carried out. Haupin has provided a detailed breakdown of energy content of aluminium and provided a value of 231.9 MJ/kg, as shown in Table 1 (Haupin, 1987). Berge reports that the production of aluminium in northern Europe consumes less than one third (31.5%) of the energy required to produce aluminium in central Europe (Berge, 2001). Following this assessment, the energy content of primary aluminium production in northern Europe is 73 MJ/kg. The present work is based on windows produced in Norway, for which aluminium used, is obtained from Sweden. The value of aluminium energy content is therefore, the one implied for northern Europe, i.e. 73 MJ per kg of primary aluminium.

Recycled or secondary aluminium requires only 7% of the amount of energy as needed for its primary production (Berge, 2001) while the former makes up around 27% of the total global production of aluminium (UNIDO, 1989). Considering the allowance for secondary aluminium, the embodied energy of aluminium used in present work is calculated to be 54.7 MJ/kg.

Table 1

The amount of aluminium used for cladding a window is calculated to be 3.62 kg. Considering the 8% waste during the profile making process, its total amount is found to be 3.91 kg, accounting for an embodied energy value of 214 MJ. In un-clad windows, aluminium strips are applied as external shield one timber frame and sash to protect them from water penetration. With aluminium cladding these protective profiles, 1.45kg in mass, are not required. Cladding of a window therefore requires an extra amount of 2.46 kg of aluminium with embodied energy value of 134.6 MJ. Considering the 27MJ for powder coating, the extra energy due to cladding is thus 161.6 MJ.

3.1.2. Powder coating

The aluminium used for cladding is 6063 alloy (having Silicon and Magnesium as the alloying elements). It is widely used within the building sector for its excellent corrosion resistance properties. The aluminium profiles of 6063 alloy used in this study are powder-coated to further improve their protection against weathering effects. The process involves a pre-coating treatment to properly clean the surface, which is critical to ensure strong and durable coating adhesion. The common pre-treatment in this respect is zinc phosphate based that produces a coating of phosphate crystals over the surface of the metal. The treated profiles are taken through a powder coating chamber where an electrostatic spraying process develops over them a 80-90 μm thick layer of powder. Profiles then travel through a furnace, which, by melting the power, delivers a strong corrosion-resistant coating.

The energy consumption in powder coating process can be mainly associated with the materials and electricity use. In terms of materials, the paint-powder is the main element to be considered. The energy values of the paint-powder and the power consumed for the coating process have been estimated to be 0.1 MJ and 26.92 MJ delivering a figure of 27.02 MJ per window.

3.1.3. Embodied energy

The energy consumed in cutting the cladding profiles, during assembling process, has been calculated to be equal to 2.363 MJ for each window. Powder coating energy has been already discussed that is 27 MJ for the whole window. The total energy embodied in cladding of a window is thus evaluated to be 243.4 MJ.

3.2. Glazing unit

In double glazed windows glazing unit mainly comprises of glass and inert gas (optional) besides components such as rubber sealing and spacer. Glass and inert gases are discussed as under.

3.2.1. Glass

The materials used for glass production vary a lot depending on the properties required for specific applications of the glass product. The fundamental glass making process and raw materials consumption is shown in Figure 4 (Edwards and Schelling, 1999). Glass is a recyclable material. Rejected parts from the moulding process have always been melted for recycling whereas post-consumer recycling is also very common practice now. The production of glass is an energy demanding process. Glass has an estimated embodied energy of 13 MJ per kg (West et al., 1994). The total mass of glass incorporated in the finished window unit has been estimated to be 21.2 kg. Considering the 5.5% waste, the total amount of glass that can be attributed to a window production is calculated to be 22.26 kg, accounting for an embodied energy value of 289 MJ.

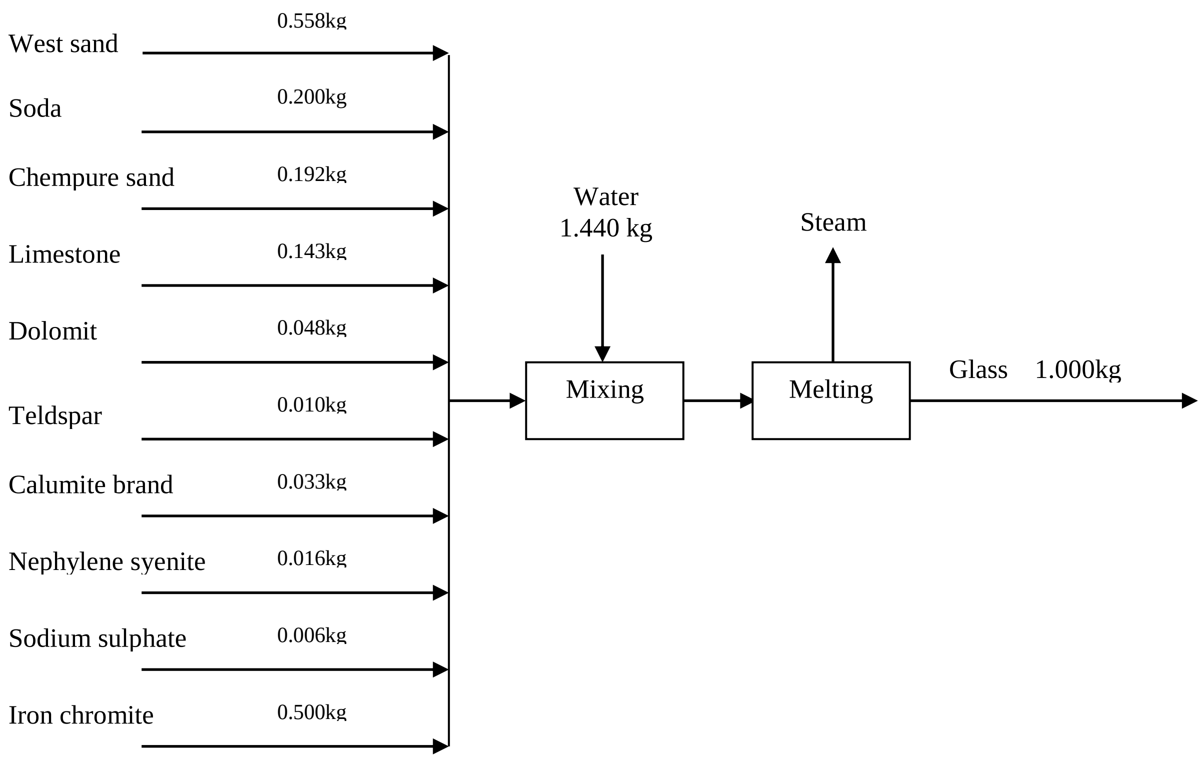


Figure 4: Production process of glass

3.2.2. Iinert infill gases

Inert infill gas or air is used in between the two glass layers of the double glazed windows to enhance the thermal resistance of the windows. Normally air or Argon (Ar) gas is used in glazing cavity although Krypton (Kr) and Xenon (Xe) gases can also be used. The cavity gap between the two layers of glass depends upon the type of the used infill gas. The greater the molecular weight of the gas the smaller the cavity gap, since the thermal conductivity drops with the increase of molecular weight. The cavity gap between the glazing layers is maintained as 16 mm, 12 mm and 8 mm for Ar, Kr and Xe respectively. The amount of gases required to fill the respective cavities is 17.6 litres, 13.2 litres and 8.8 litres with embodied energy values of 0.01MJ, 502.8 MJ, and 4500 MJ (Muneer and Fernie, 1995).

3.3. Timber

Softwoods demonstrate useful characteristics for their wide ranging applications in the building industry. For example, these are fast-growing, durable and easy to process. They have good strength-to-weight ratios and deliver good surface finishes. For the windows under consideration in this study, their frame and sash components come from different species of softwood such as Baltic Pine and Redwood. To enhance its service life and boost its resistance against wide ranging potential threats such as warping, rot, fungi and insect attacks, wood goes through treatment processes like vacuum impregnation. The embodied energy value for softwood timber is around 2.6 GJ/m^3 (West et al., 1994).

Taking into account the relevant wastes, the required amount of timber is 37 kg (frame: 14.9 kg, sash: 10.0 kg and waste: 12.1 kg). The density values of softwood can vary significantly depending upon its water content. For the timber used in this study, having a density value of 500 kg/m^3, the energy content involved in the complete window, excluding the machining process, is calculated to be 192.4 MJ. For sash sections, the laminating process involves gluing and compression of two or three sections of timber together. The estimated energy content of glue used in the analysed window is 2.94MJ, which brings the total embodied energy of timber frame and sash in the whole window to an amount of 195.3MJ.

3.4. Other aluminium components used

There are various aluminium components used in a window including glazing spacer, frame ventilation system and window adjusting mechanism. The net mass of these components is estimated to be 0.57kg/window while taking into account an average waste of 9%, the total mass turns out to be 0.64kg/window.

3.5. Manufacturing and assembly

3.5.1. Timber frame and sash

Window sash and frame are made of timber. Timber profiles are processed on various saw, milling and pressing machines. After the sashes and frames are prepared, they are vacuum impregnated to enhance their durability and service life. The energy consumption value for the production of each set of frame and sash has been calculated to be 16.3 MJ and 16.9 MJ respectively, providing a total timber manufacturing energy of 33.2 MJ (Weir and Muneer, 1998).

3.5.2. Sealed glazing unit

This process involves the cutting of glass panes with precision on a CNC glass-cutting machine, washing, fixing the aluminium spacer, filling the infill gases and sealing the whole unit. The analysis shows an energy consumption of 6 MJ in producing one sealed glass unit.

3.5.3. Factory services

Factory services consume a significant amount of energy in terms of lighting and heating that has been estimated to be as much as 97.7 MJ per window as indicated in Table 2.

Table 2

3.6. Total embodied energy of an aluminium-clad timber window

Aluminium, glass and timber are the three major energy expensive materials in a window. In terms of infill gases, Argon requires only a small amount of energy to be produced; Krypton consumes a considerable amount of energy, while Xenon requires the greatest amount of energy. Taking into account all these factors within the boundaries of this assessment, the embodied energy of a standard aluminium-clad timber window has been respectively calculated to be equal to 899 MJ, 1402 MJ, and 5400 MJ with Ar, Kr and Xe gases, as shown in Table 3.

Table 3

The extra energy associated with introducing aluminium cladding, 161.6 MJ, brings an additional 21.8%, 13% and 3% of energy content for Argon, Krypton and Xenon based windows respectively as indicated in Figure 5.

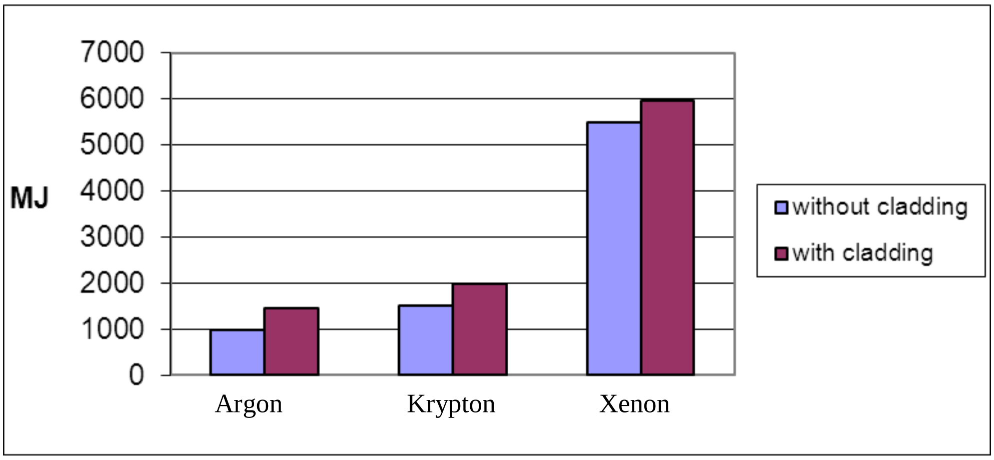


Figure 5: Embodied energy comparison of timber windows with and without aluminium cladding for three infill gases

4. ENVIRONMENTAL IMAPCT

Every material and process involved in window production contributes to environmental loads to some extent. The scope of this study covers the following materials as the major loads inflicting entities: aluminium, timber, glass and infill gases.

4.1. Aluminium

The production of aluminium from ore, also termed as primary aluminium, is generally categorized into four distinctive stages - mining of ore (bauxite), refining, smelting and finishing. These processes, due to the materials and energy involved, are critical in the life cycle assessment of aluminium. The production of recycled or secondary aluminium is a relatively simple process requiring less energy as compared to primary aluminium. Figure 6 shows the basic processes involved in the production of primary aluminium, also, highlighting the material inflow and waste generated at each stage (Habersatter, 1991).

Production of aluminium is an energy intensive activity, which in itself brings significant environmental burdens on top of the pollutants generated during the process. Wide ranging pollutants are released during the production of aluminium such as carbon dioxide (CO_2), polyaromatic hydrocarbons (PAHs), sulphur dioxide (SO_2), tetrafluoromethane (CF_4), perfluorocarbons (PFCs) and hexafluoroethane (C_2F_6) (Berge, 2001) (IAI, no date). These pollutants whether washed-off into watercourses or released into air, cause implications for the surrounding environment and human population.

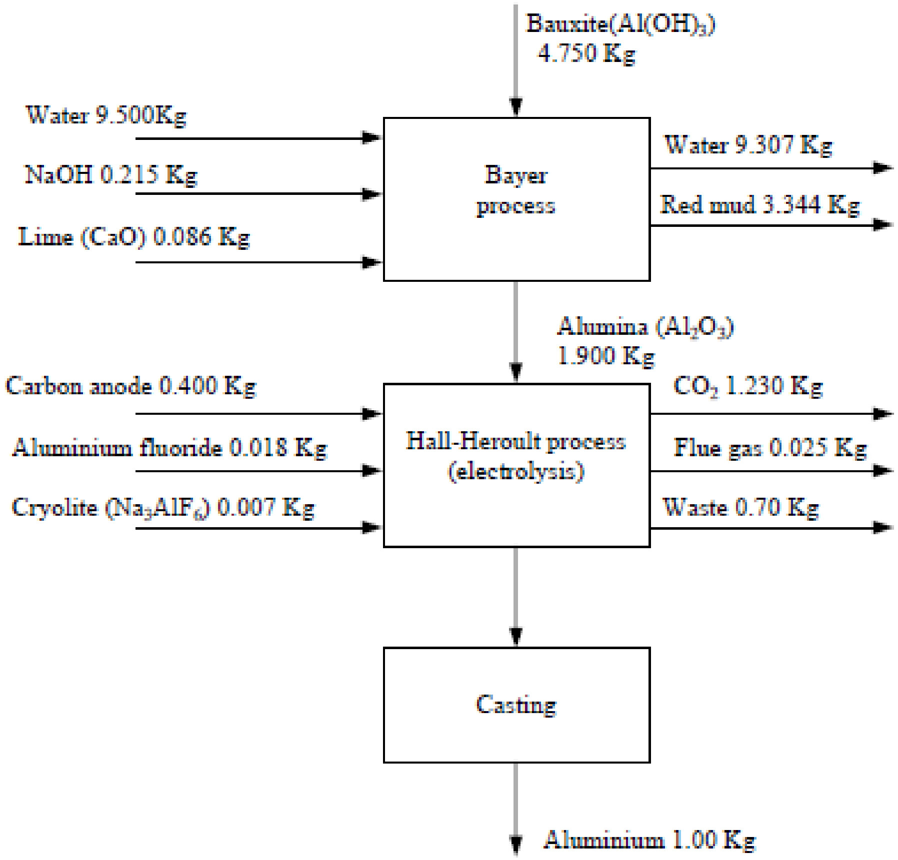


Figure 6: Primary aluminium production from raw material

The production of primary aluminium has a high embodied energy value due to the involved process of smelting alumina into aluminium. Its easy recyclability is one of aluminium's major advantages. It can be repeatedly recycled without any compromise on quality. The more frequently it is recycled the better its lifetime cost competitiveness becomes.

4.2. Timber

Trees are critical for sustaining life for their photosynthesis process. They contribute to sustainability in several indirect ways. Forests, for example, positively influence local climatic conditions, also by contributing to rainfall. Plantation also help in mitigating the land erosion thus providing a protective barrage against flooding. Timber is one of the most commonly used and traditional construction material. Use of timber for construction is regarded as an environmentally sound choice. There is growing global awareness about forest protection and many countries have robust forest management programs in place implying that every downed tree is replaced by a new one. Trees during their period of active growth (younger trees) have higher tendency of carrying out photosynthesis, hence are regarded as more friendly for environment. The softwood considered in this study is also environmentally controlled, and regarded as a renewable resource, as it comes from the Scandinavian countries having an effective tree management programs in place. Also, timber is regarded as a recyclable material because towards the end of originally designed service life, it can be down-cycled to for applications such as chipboard production and garden projects. Timber remains from windows are usually disposed-off in various ways including incineration, land filling and down-cycling.

4.3. Glass

The environmental impacts of glass are associated with its production phase, which is energy intensive. Glass manufacture, which involves heating the batch to high temperatures, makes use of large quantities of oil, gas or electricity. All these fuels involve, at some point, the release of CO_2 and other gases. Pollution can also occur from quartz dust and calcium chloride. Hydrogen fluoride and hydrogen chloride are also emitted on top of tin pollution during the vapour deposition of tin oxide. Glass does not cause any pollution during its use, however, after its disposal arsenic trioxide and antimony trioxide can seep out leading to environmental pollution. The overall global warming potential (GWP) of glass is 569g/kg. Table 5 shows pollution generation tendency of the basic constituents of an aluminium-clad timber window, i.e. aluminium, glass and timber (Berge, 2001).

4.4. Infill gases

Argon (Ar), Krypton (Kr) and Xenon (Xe) are present in atmosphere in small proportions. A schematic diagram of the BOC gas production unit at Middlesbrough is shown in Figure 7. Extraction of Krypton and Xenon are energy extensive processes. These gases reduce the thermal heat loss from the window resulting into overall energy saving.

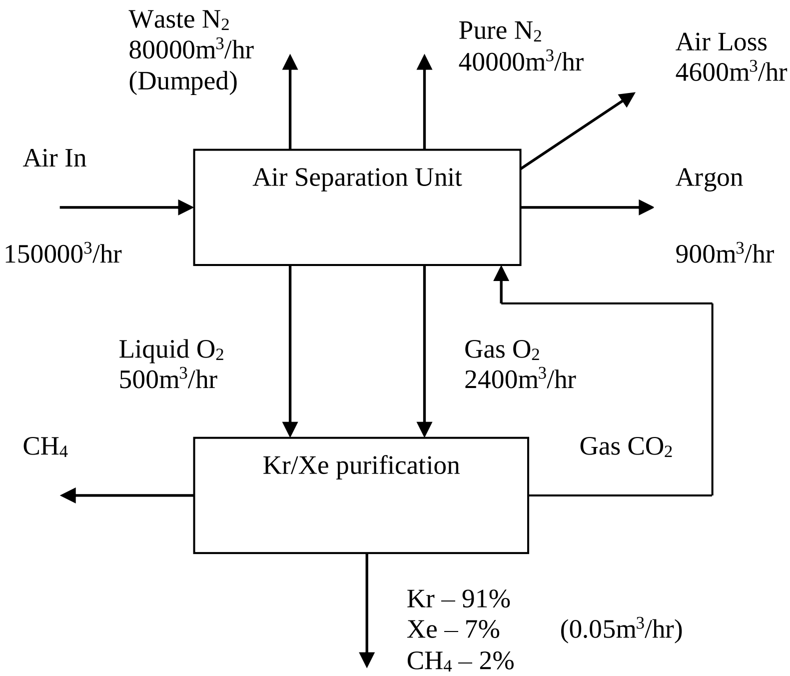
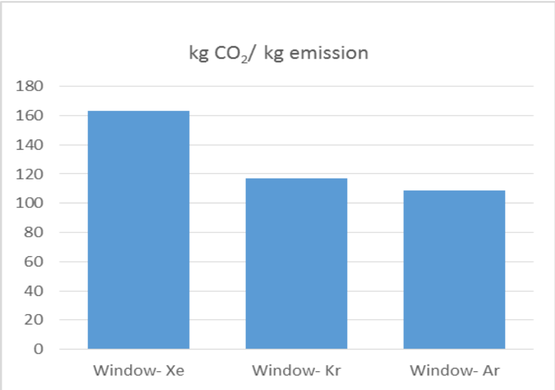


Figure 7: Schematic of gases production process

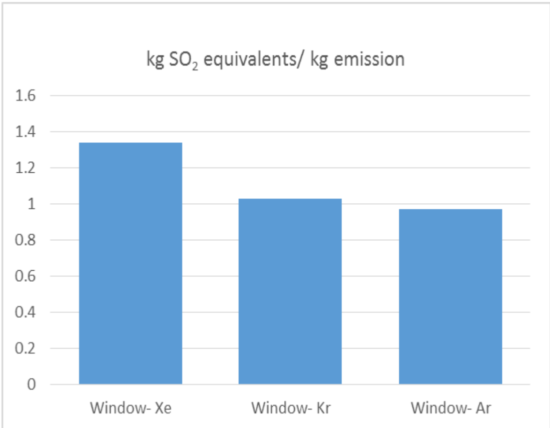
Production of Kr and Xe is an energy intensive process and hence these gases account for the largest share in the production of the respective double glazed windows as highlighted in Table 3.

4.5. Production Phase

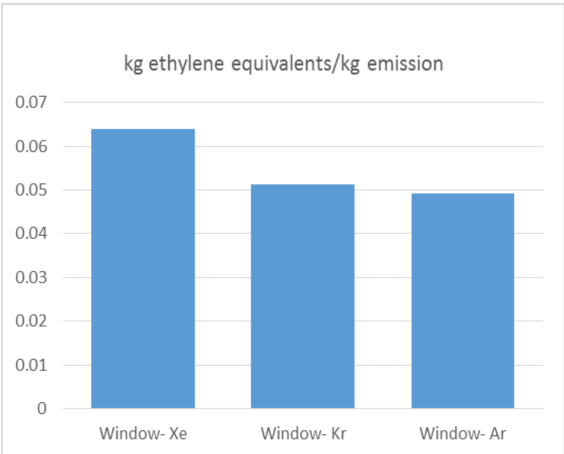
The production phase analysis has been carried out with the help of SimaPro (v: 8.05.13). Within SimaPro, Ecoinvent database (v: 3.0) is used for material modelling, and Environmental Product Declaration (EPD) method has been used as the impact assessment technique. The EPD method is recommended by EN 15804 with a complete guideline for estimating environmental impacts and has been used in several LCA studies (Roh et al 2017; Asif et al 2017; Li et al 2013). A comparative assessment of the three windows reveal that Argon filled windows have the least environmental impacts under all of the three categories: GWP, acidification potential and photochemical oxidation as shown in Figure 8.



(a). Global warming potential



(b). Acidification potential



(c). Photochemical oxidation

Figure 8: Environmental impacts from double glazed windows

Xenon filled windows have been found to be exhibiting the highest environmental burdens, and it is due to the energy intensive production of the gas itself. Figure 9 provides proportional emissions by the materials involved in frames of the studied windows in terms of impacts on human health, ecosystem and natural resources. It can be seen that aluminium has the greatest environmental burdens followed by glass. Both these materials are quite demanding in terms of production stages and the involved energy content. In terms of impacts on ecosystem, timber bears the heaviest burden followed by aluminium and glass.

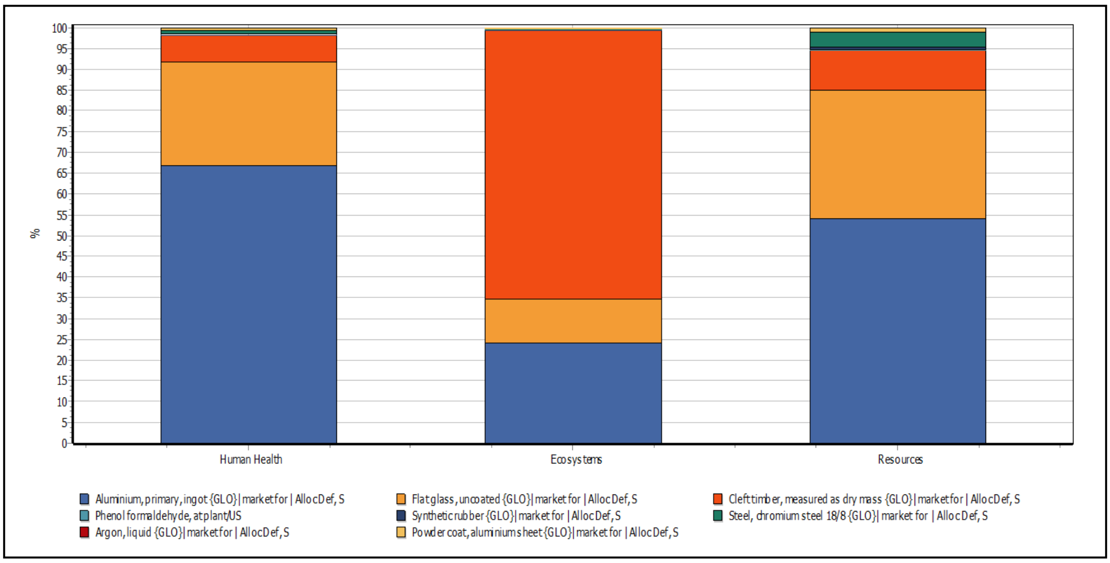


Figure 9. Proportional impact of window frame materials on ecosystem, resources and human health

4.6. Operational phase

The environmental performance of windows during the operational phase has been determined in terms of their heat loss. Windows with low U-value result into reduced heat loss and environmental emissions. The U-values of Ar, Kr and Xe filled windows have are 2.1 W/m^{2}K, 1.6 W/m^{2}K and 1.2 W/m^{2}K respectively as calculated with the help of the equation (ASHRAE, 2009):

$$U_o = (U_{cg}A_{cg} + U_{eg}A_{eg} + U_f A_f)/A_{pf}$$

Where

U_o = Overall *U*-value of window (W/m^{2}K)
U_{cg} = Centre-of-glass *U*-value (W/m^{2}K)
U_{eg} = Edge-of-glass *U*-value (W/m^{2}K)
U_f = Frame *U*-value (W/m^{2}K)
A_{cg} = Area of glazing (m^2)
A_{eg} = Area of edge-seal (m^2)
A_f = Area of frame (m^2)
A_{pf} = Area of the fenestration (m^2)

The energy consumption for the windows has been calculated for an example office building. The analysis makes several assumptions in terms of the office environment, location, orientation and construction. It is assumed that under typical operating conditions, a set point temperature of 19C is maintained in the office. The reference office is situated on the middle floor of a three storey building located in Edinburgh, UK, and has one south facing external wall. The considered office is surrounded by spaces from below, above and all internal sides with same temperature. The office space is heated throughout the heating season (1 October to 30 April in northern hemisphere), over the 8a.m. to 6 p.m., the windows are open-able to provide natural ventilation during summer months avoiding the need for artificial cooling. The analysis is based upon their annual energy consumption or heat loss calculation for an operational life cycle of 30 years as shown in Table 4.

Table 4

The life cycle heat loss from Argon, Krypton and Xenon filled windows has been calculated to be 95,130 kWh, 72,480 kWh and 54,360 kWh respectively. Environmental impacts are expressed in terms of CO_2 emission taking into account both electricity and gas as heating sources. It can be seen that gas based heating system results into less than half of emissions as compared to an electricity based one. The power generation mix of UK has been used to calculate the CO_2 emissions associated with electricity.

5. CONCLUSIONS AND DISCUSSION

Life cycle assessment is an important tool that can help improve the sustainability standards in the building sector. The present study examines double glazed aluminium-clad timber windows with three different infill gases to determine the environmental impacts associated with their production and operational phase. The environmental performance of windows is dictated by not only their embodied energy but also the energy used during their operational phase. Aluminium clad timber windows are relatively new in the market as compared to timber, PVC and aluminium windows. This type of frame combines the advantage of timber and aluminium in the form of sustainability and durability - aluminium cladding offers an extra layer of weather protection reducing the maintenance requirements and increasing the life span of the timber frame. The energy use during the operational phase of windows is significantly influenced by the composition of glazing. The study takes into account the materials and processing involved in the manufacturing of these windows in order to calculate their embodied energy and associated environmental impacts. Findings of the work reveal that the embodied energy of a standard sized (1.2m x 1.2m) double glazed aluminium-clad timber window is 899 MJ, 1,402 MJ, and 5,400 MJ for Argon (Ar), Krypton (Kr) and Xenon (Xe) infill gases, respectively. Of the window frames, aluminium and glass are the two most significant materials in terms of embodied energy and environmental impacts. Infill gases can make a major difference in the energy and environmental performance of windows. Xenon and Krypton filled windows, for example, respectively offer 75% and 31% saving in heat loss as compared to those filled with Argon. An investigation of its operational phase reveals that over a 30-year period an Argon filled window can lose 95,130 kWh of energy resulting into over 37,000 kg of CO_2 emissions. The study reveals the vital contribution of inert gases. Kr and Xe based windows are found to have around 500MJ and 4500MJ of higher embodied energy respectively compared to an Argon filled window. The extra embodied energy however pays itself back manifold during the operational phase – Kr and Xe filled windows are found to respectively save 81,540MJ and 146,772 MJ of energy. It is thus evident that the operational phase of a window is more important than its production.

The building industry across the world is pursuing sustainable development in its response to the growing energy and environmental challenges (Lu & Lai, 2019; Nahid et al 2018; Sadiq; Khan and Asif 2017). The sustainability drive is being propelled by ever stringent building regulations requiring improved energy efficiency and environmental performance. In the UK for example, the minimum U-value in 1970s used to be around 4.8 W/m^2K. The current regulation, Part L1A for new dwellings, gives a target value U value of 1.4 W/m^2K and a minimum requirement of 2.0 W/m^2K (BRE, 2019; HMG, 2010). The results and findings of this study advocate for the effectiveness of multi-glazed windows as a sustainability measure to improve the energy and environmental performance of buildings. Energy efficient windows can help buildings meet stringent energy standards as required in continuously evolving regulations. The role of multi-glazed windows with inert infill gases is more critical in harsh climates with extensive heating or cooling load. Findings of the study can help the window industry opt for environmentally more sustainable design options. The wider construction industry can also benefit from it in terms of selecting sustainable materials. The study can also be of help to public sector bodies and institutions dealing with concerned standards and legislations. Reduction in environmental emissions from the building sector as a result of use of energy efficient windows can also help countries meet their international environmental obligations.

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