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Estimate of energy consumption and CO_2 emission associated with the production, use and final disposal of PVC, aluminium and wooden windows

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1 Summary

Windows provide a series of services in homes and buildings. One of the most important of these is thermal insulation, to prevent flows of heat and cold and to maintain the corresponding levels of heating and climatization.

The material of the structural frame influences the insulating capacity of the window, and there is interest to discover the environmental impact of the choice of material in all the window's life cycle stages. The following materials have been considered in this paper: PVC, aluminium and wood. It is assumed that, at the end of the window's use period, the materials are recycled; i.e. it is considered there is no direct reuse of them. In this analysis, a usable lifetime of 50 years has been allocated to all the windows, assuming that the PVC, aluminium and wooden structures (with the relevant maintenance) retain their functional properties.

The evaluation of the environmental impact has been carried out taking the following fundamental indicators into account: (1) estimate of energy consumption; and (2) emission of carbon dioxide (CO_2) attributable to the manufacture, use, recycling and final disposal of waste materials, for windows with a structural frame made mainly of PVC, aluminium or wood.

The analysis is based on a standard casement window measuring 1.34 m x 1.34 m, double glazed, installed in a standard room, which is manufactured and used in the sphere of the Iberian Peninsula. Given that wooden windows with single glazing are widely used in Spain, this alternative has been included as an eighth case of complementary analysis.

The methodology used is based on a procedure for environmental accounting of energy consumption figures and CO_2 emissions, in which these indicators have been estimated in each of the stages of the life cycle of a window made of PVC, aluminium or wood (extraction and production, transport to assembly, assembly, transport to building, use, transport to disposal site, disposal in disposal site, transport to recycling and recycling). The end results signify the equivalent sum of the energy consumption and CO_2 emission figures for each of these stages.

The results obtained indicate that, in all the cases analysed, the highest percentages of energy consumption (between 42 and 97%) correspond to the stage of use of the window. This consumption refers to energy losses through the window. The energy consumption figures in the stages of extraction and production of materials are considerable for aluminium windows (up to 52% of the total); this percentage is lower for PVC (14%) and wooden (4%) windows.

The PVC window with 30% recycled material presents the lowest energy consumption (1,740 kWh) and CO_2 emissions (730 kg). The PVC window with no recycled material presents consumption of 1,780 kWh and CO_2 emissions of 742 kg.

Next would come the wooden window with double glazing, presenting consumption of 2,045 kWh and CO_2 emissions of 886 kg; followed by the wooden window with single glazing, with energy consumption of 2,549 kWh and CO_2 emissions of 1,129 kg.

Lastly, the highest values of energy used and CO_2 emissions correspond to aluminium windows. The windows with 30% recycled aluminium present energy consumption of 3,244 kWh, and 3,838 kWh in the case of windows with and without thermal break. These windows present CO_2 emissions of 1,418 kg and 1,681 kg, respectively. For the case of windows not using recycled aluminium, the energy consumption figures represent 3,819 kWh and 4,413 kWh for windows with and without thermal break; in this order, they present CO_2 emissions of 1,672 kg for the window with thermal break, and 1,935 kg in the case of the aluminium window without thermal break.

As regards recycling of the window materials, the wooden window with double glazing provides 21.4 kg of recycled material in the recycling stage, from the glass (62% of the total weight of the window). In the case of the wooden window with single glazing, only the glass can be recycled (10.7 kg; 45% of the total weight). To the contrary, the PVC and aluminium windows provide 49.2 kg and 62.2 kg, respectively, from both the glass and the frame (93 and 94% of the total materials, respectively). So, there is greater availability of recycled material to make a new window, or for these materials to be used in other products. In the case of the wooden windows, since the frame cannot be recycled, new wood has to be extracted and treated.

2 Background

Windows, as architectural elements of homes and buildings, fulfil a series of functions, including the following:

- Acting as a connecting element between the inside and outside of the home.
- Supplying both natural lighting and thermal insulation, assisting adequate climatization.
- Offering protection against bad weather conditions.
- Offering protection against other external factors, such as noise, atmospheric pollution, insects, etc.
- Security/safety.

Windows normally take up between 10 and 25% of the surface area of the exposed walls. Glass, as a transparent element, allows daylight into the home, and it is integrated into the building with a structural frame.

When choosing a particular type of window, the most widely used and best known materials, the use of materials, the architectural design, and the costs of construction and maintenance are usually considered.

The material of the structural frame, the type of glass, the design of the window and the use of single glazing (one single pane of glass) or multiple glazing (two or more panes of glass), are elements with a direct bearing on the window's level of thermal insulation.

This last characteristic is important in middle or high latitude countries. In winter, energy consumption required to maintain a comfort temperature inside homes is major. In Spain, electrical heating systems in homes use on average 8% of total electricity consumed by the residential sector on a typical winter's day (REE, 2004). The improved thermal insulation characteristics of the wall/window system signify less electricity consumption to maintain a determined level of climatization.

Over recent years, with the gradual implementation of more restrictive environmental legislation on emissions into the atmosphere (primary pollutants and greenhouse gases), the promotion of energy efficiency, clean production and the use of the best techniques available, interest has been growing in objectively analysing the environmental impact consequent to the manufacture, use and final disposal of waste materials for windows made of different materials.

Traditionally, wood has for many years been the material used to make structural frames. Aluminium is also a widely used material. Over recent decades, the use of PVC structures has been considerable, particularly in Northern European countries. In Germany, in 2003, use of PVC reached 49%, versus 28% for wooden frames, 20% aluminium, and 3% for aluminium/wooden frames (EC, 2004). In Spain, over recent years, the breakdown of materials is as follows: aluminium (73%), wood (13%), PVC (11%), and others (3%).

The environmental implications of windows are the subject of study in different countries. However, in view of the complexity of the analysis, there are few studies, and the majority of them have different focuses (Chevalier *et al*., 2002). These contributions focus on Northern European countries and the USA.

The conditions of analysis can vary, if we consider the variety of sizes, shapes or configurations windows can have, even in the same home. A pragmatic method of analysis is to focus the study on a window with fixed dimensions (Asif *et al.*, 2002; Weir and Muneer, 1998) .

2.1 Objective and calculation bases

This document presents an estimate of energy consumption and carbon dioxide (CO_2) emission attributable to the manufacture, use, recycling and final disposal of waste materials, for windows with structural frames made of PVC, aluminium or wood.

This focus is based on a consideration of all the stages of a Life Cycle Assessment (LCA) study, although the scope focuses on the two environmental factors (indicators) cited above.

In order to make it possible to produce an analysis enabling comparative results to be obtained, an openable window measuring 1.34 m x 1.34 m is used as the unit of analysis (the functional unit in an LCA study), with the same characteristics for the different materials considered.

The results aim to be representative for the Iberian Peninsula, whereby priority is given to the information and conditions of this region, in the analysis that follows.

2.2 Contents of the document

A description is given of the stages comprising the window's life cycle, and likewise the calculation hypotheses and scenarios for the comparative analysis. The most significant energy consumption values are indicated, and likewise the conformation of the energy sources defining the CO_2 emission factors. The estimate of energy consumption in the use stage of the window is presented in particular detail.

The results obtained are included in detail and summary form. The estimates obtained are analysed, and the alternatives with the lowest energy consumption and CO_2 emission values are identified, in ascending order.

3 The life cycle of a window

Figure 3.1 shows the typical life cycle of a window, focusing on use of energy and the corresponding emissions into the atmosphere.

The methodology used is based on a procedure for environmental accounting of energy consumption figures and CO_2 emissions, in which these indicators have been estimated in each of the stages of the life cycle of a window made of PVC, aluminium or wood (extraction and production, transport to assembly, assembly, transport to building, use, transport to disposal site, disposal in disposal site, transport to recycling and recycling). The end results signify the equivalent sum of the energy consumption and CO_2 emission figures for each of these stages.

The first stage consists of the phase of extraction of raw materials and obtention of the elements of the window. These components are put together in an assembly plant.

The stage of use of the window is the longest. For PVC and aluminium windows, mean lifetimes of 50 years are usually considered, without any major energy consumption requirement for their maintenance. For wooden windows, shorter lifetimes are usually considered, and protective coatings (varnish, paint) need to be applied once every 2 years. In this study, it will be assumed that all the windows have a usable lifetime of 50 years, and that this maintenance has been carried out systematically.

Once the window's use period is over, it is then deconstructed and transferred to a recycling centre. The non-recyclable portion is sent to a final waste disposal management centre.

Depending on the material, production of the structural frames can present particular stages. For example, Figure 3.2 shows, in detail, the stages of production and use of PVC structures. PVC resin is mixed with certain additives to produce pellets. This mixture is subjected to a process of hot extrusion, which produces the actual frame. This frame is sent to the window assembly plant, where it is assembled with the other elements (panes of glass, steel reinforcement, waterproof seals and lock fittings).

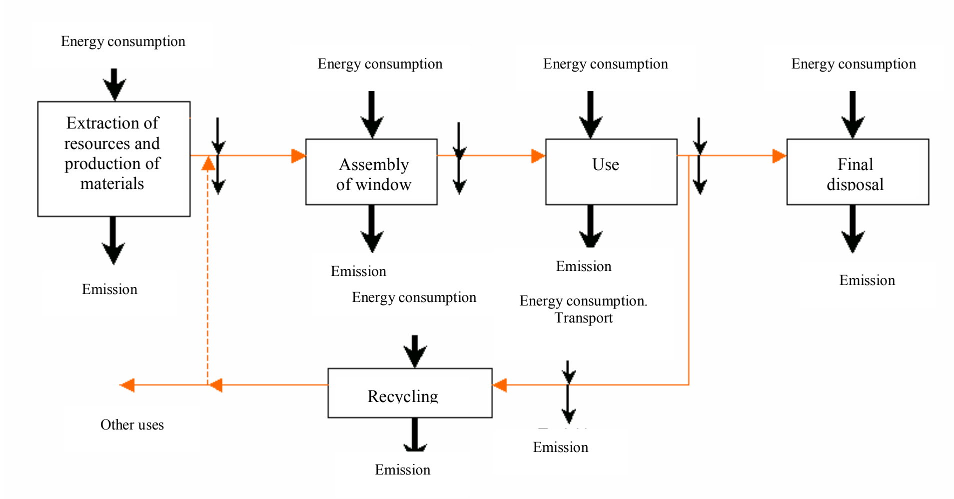

Figure 3.1: The life cycle of a window

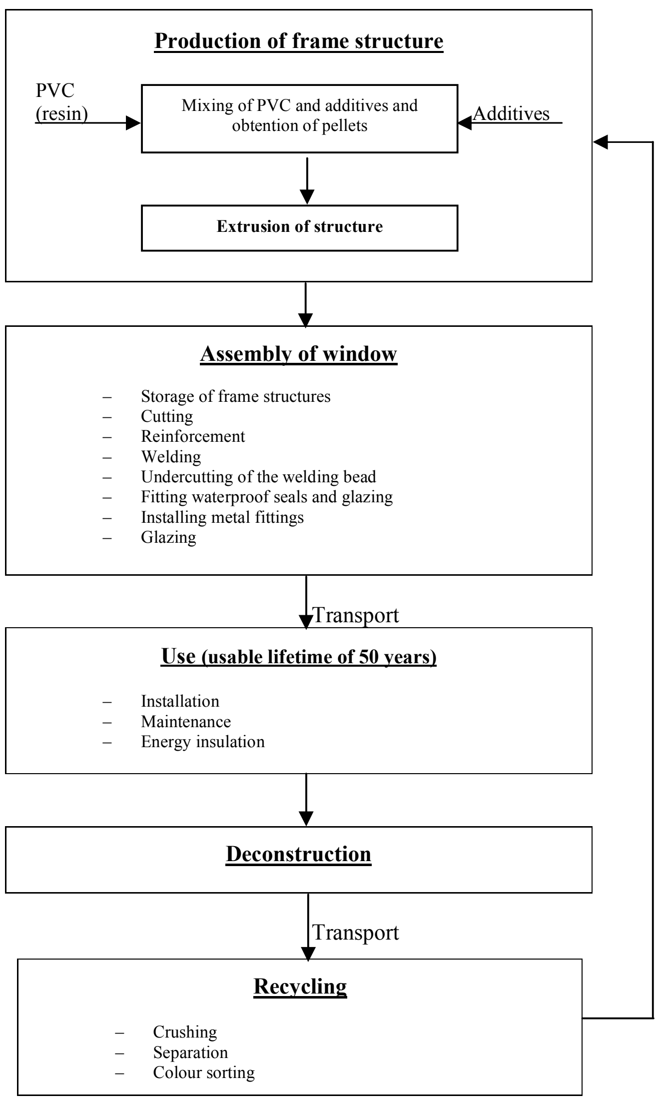

Figure 3.2: Stages of PVC structure production and use for windows

4 Estimate of energy consumption and CO_2 emission attributable to a window measuring 1.34 m x 1.34 m

4.1 Calculation bases

4.1.1 Dimensions

In order to be able to produce an analysis enabling comparative results to be obtained, an openable or standard casement window measuring 1.34 m x 1.34 m is used as the unit of analysis.

4.1.2 Materials of the structural frame

Basically, the analysis focuses on the estimate of energy consumption and the corresponding CO_2 emissions, for the window with the measurements as defined, with its structural frame made of three alternative materials:

- PVC
- Aluminium
- Wood

4.1.3 Glazing

It is considered that the windows are double-glazed, this comprising two panes of normal glass 4 mm thick, with an air cavity of 6 mm or 12 mm, depending on the window.

4.2 Scenarios analysed

The following cases are analysed:

1) PVC window, with double glazing 4/12/4, the structural frame of which does not include recycled PVC
2) PVC window, with double glazing 4/12/4, the structural frame of which includes 30% recycled PVC
3) Aluminium window without thermal break, with double glazing 4/6/4, the structural frame of which does not include recycled aluminium
4) Aluminium window without thermal break, with double glazing 4/6/4, the structural frame of which includes 30% recycled aluminium
5) Aluminium window with thermal break, with double glazing 4/12/4, the structural frame of which does not include recycled aluminium
6) Aluminium window with thermal break, with double glazing 4/12/4, the structural frame of which includes 30% recycled aluminium
7) Wooden window, with double glazing 4/6/4.
8) Wooden window, with single glazing.

Case number eight (single-glazed wooden window) is included to cover the use of this type of window in the area of the study. In Spain, the use of double-glazed wooden windows is negligible.

4.3 Extraction and production of materials

This consists of the energy required for the extraction of natural resources, transport to the factory and production of the materials used in the window, mainly: frame in PVC, aluminium, wood; glass, lock fittings and additives.

For the PVC frame, we have used the energy consumption and CO_2 emission presented in the document "*Estimate of the energy consumption and CO_2 emission associated with unit production of PVC*" (Baldasano & Parra, 2005). We have used the values of the calculation criterion that considers the joint obtention of PVC and caustic soda. The energy consumption for the manufacture of PVC is 7.19 kWh kg^{-1}; and the associated CO_2 emission factor is 2.04 t CO_2 t^{-1}PVC.

The energy consumption figures for other materials correspond to the production of steel, glass, aluminium and wood.

For steel, an energy consumption of 6.70 kWh kg^{-1} is assumed, obtained from the production energy consumption (5.03 kWh kg^{-1}) from the European BREF document on iron and steel (EPA, 2004), considering that this second value is 75% of the energy consumption for extraction, transport and production of the steel. It is assumed that the energy used is made up of 92% coal and 8% electricity.

For glass, an energy consumption of 2.70 kWh kg^{-1} is used, obtained from the production energy consumption (2.03 kWh kg^{-1}) from the European BREF document on glass (EPA, 2004), considering that this second value is 75% of the energy consumption for extraction, transport and production of the glass. It is assumed that the energy used is made up of 89% fuel-oil/diesel and 11% electricity.

For aluminium, an electricity consumption of 45.56 kWh kg^{-1} is assumed, and this includes energy consumption for extraction of the minerals, treatment of the alumina and final production of the aluminium (WBG, 2004).

For wood, an energy consumption of 0.58 kWh kg^{-1} is used, and this includes extraction, transfer (250 km) and drying. The information on timber extraction and drying consumption is taken from the Simapro5 database. It is assumed that 92% of the energy comes from diesel fuel and that 8% is electrical energy.

The energy consumption figures for the materials are summarized in Table 4.1.

Table 4.1: Energy consumption figures for extraction of natural resources and production of materials

Material	Energy consumption ($kWh\ kg^{-1}$)	Source
PVC	7.19	(Baldasano & Parra, 2005)
Steel	6.70	(EPA, 2004)
Glass	2.70	(EPA, 2004)
Aluminium	45.56	(WBG, 2004)
Wood	0.58	Simapro5 database

4.4 Assembly of the window

For windows made with PVC frames, an energy consumption of 0.22 kWh (kg PVC)$^{-1}$ is assumed, this figure was provided by the Spanish PVC Windows Association (Asoven); and it corresponds to an energy consumption of 4.8kWh per window assembled.

For aluminium and wooden frames, the same value of 4.8 kWh per window assembled was used; it was assumed that the energy consumption for assembly is similar for all the windows. For assembly of all the windows, it is considered that the energy used is electrical.

4.5 Use of the window

To estimate the energy consumption in the use stage, a standard room for analysis was considered, with the window located on one outside wall. its dimensions are indicated in Figure 4.1. The volume of air contained in the room is 32.4 m^3 (3 m x 4 m x 2.7 m). The wall/window system has a surface area of 8.1 m^2 (3 m x 2.7 m), with 1.80 m^2 corresponding to the actual window (1.34 m x 1.34 m); i.e. 22 %.

The quantity of heat to be supplied to or extracted from the room's volume of air must be that required to:

1) Raise (in winter) or lower (in summer) the temperature of the air inside to a comfort level, which is assumed to be 22ºC, the value recommended by the Technical Building Code (MFOM, 2004).

2) To maintain the temperature of the air inside at 22ºC during the mean staying time in the room. Maintaining this temperature signifies continuously supplying or extracting heat to and from the air inside, to offset the heat flow through the exterior wall/window system.

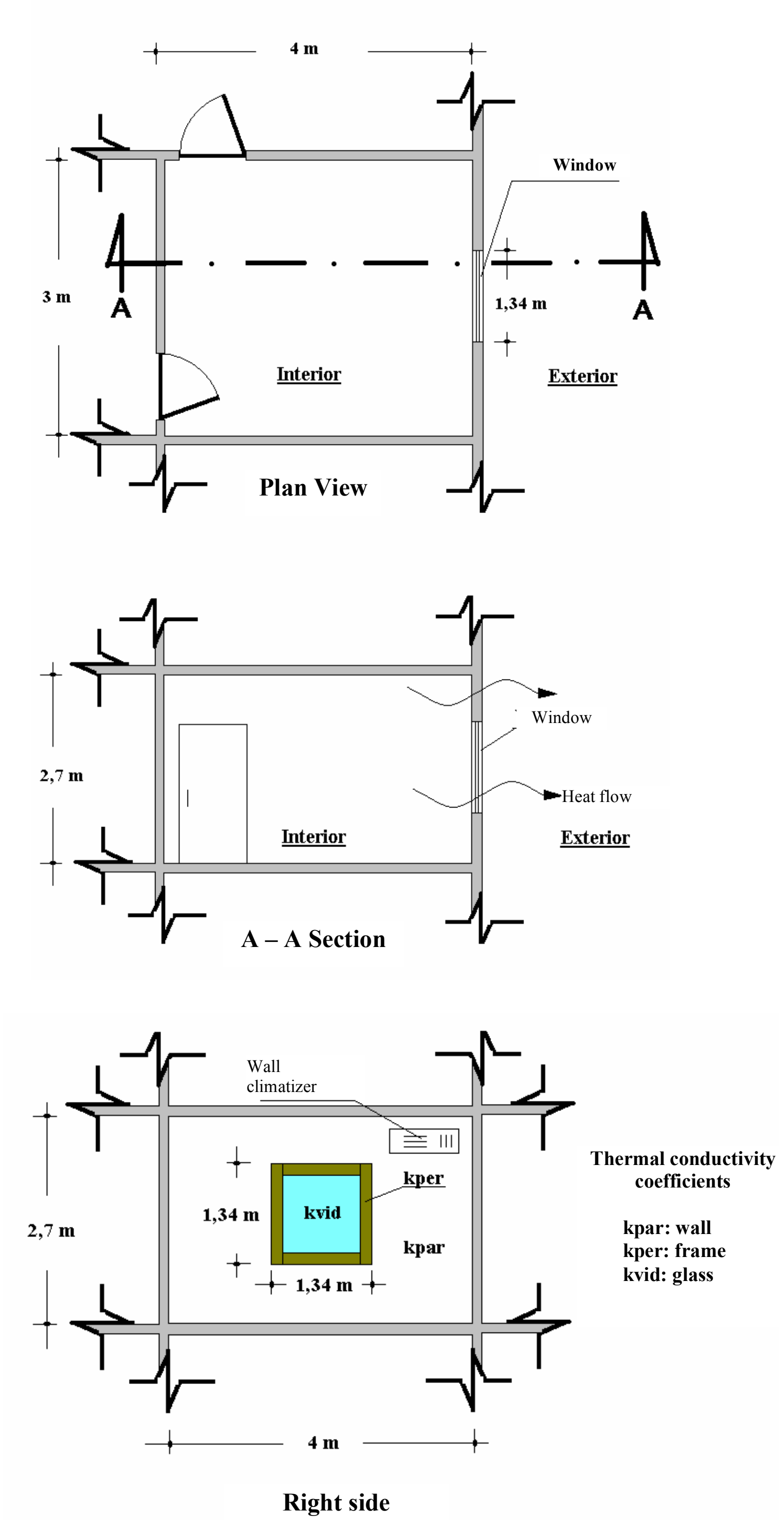

Figure 4.1: Dimensions of the room subject to analysis

To simplify the analysis, it is considered that the exterior wall containing the window is the sole route for heat loss or gain; i.e. it is assumed that there is no energy flow through the interior walls, floor or ceiling.

It is assumed that the heating or cooling used is a split window air-conditioner system. These appliances are usually able to supply or reduce heat at levels of 2-3.5 times the electrical energy they use (Morrison, 2004). In this study, a value of 2.6 is assumed.

4.5.1 Thermal conductivity of the wall/window system

For the definition of the thermal conductivity coefficients, according to the different materials of the window's structural frame, the surface contribution of the wall, of the actual structural frame and of the glass is considered, according to the data in Table 4.2.

Table 4.2: Surface areas of the wall/window system

Component	m^2	%
Surf. area of wall (A_{par})	6.3	77.8
Surf. area of frame (A_{per})	0.5	6.2
Surf. area of glass (A_{vid})	1.3	16.0
Total:	8.1	100

The thermal conductivity coefficients were taken from the Technical Building Code (MFOM; 2004) (Table 4.3). The value of the integrated coefficients of the wall/window system ($U_{wall/window}$) indicated in Table 4.4 are calculated using equation 1.

$$U_{wall/window} = \frac{A_{par}.U_{par} + A_{per}.U_{per} + A_{vid}.U_{vid}}{A_{par} + A_{per} + A_{vid}} \quad (1)$$

Table 4.3: Thermal conductivity coefficients (MFOM, 2004)

Component	$W\ m^{-2}\ °C^{-1}$
Wall (U_{par}), masonry	1.63
PVC frame (U_{per})	2.00
Aluminium frame without break (U_{per})	5.88
Aluminium frame with break (U_{per})	4.00
Wooden frame (U_{per})	2.50
Single glazing (U_{vid})	5.90
Double glazing (U_{vid})	3.30

Table 4.4: Thermal conductivity coefficients of the wall/window system

Type of window	W m^{-2} °C^{-1}
PVC with double glazing	0.65
Aluminium without break, double glazing	0.89
Aluminium with break, double glazing	0.77
Wooden with double glazing	0.68
Wooden with single glazing	1.14

Likewise, the results have been considered assuming that the thermal conductivity of the wall has a value of U_{wall} equals zero; i.e. assuming there are no heat losses through the wall, in order to highlight the energy consumption and CO_2 emission values associated solely with the window in the analysis.

4.5.2 Exterior atmospheric temperature

In order to estimate the energy demand in different regions of Spain, three regions were selected with different ranges of climatological temperatures. Figure 4.2 shows the mean monthly temperatures in Prat de Llobregat (Barcelona), Madrid and Alicante; these were obtained from the monthly records for the years from 1997 to 2002, from the National Institute of Statistics (INE, 2004).

The temperature curve for Prat de Llobregat presents the most reduced temperature values (ranging from 10 to 23ºC). The temperature curve for Madrid presents the lowest winter values, although the summer temperatures are relatively high (ranging from 7 to 25ºC). Alicante, the region with the lowest latitude of those selected, presents the highest temperatures, in both winter and summer (ranging from 13 to 26ºC).

4.5.3 Estimate of losses through air permeability

Air permeability is extremely important, since heat loss from rooms and, therefore, the comfort level, depend on this. For the three regions of the study, losses due to air permeability of windows were estimated. Air permeability is the property of a window to allow passage of air when submitted to a differential pressure. Air permeability is characterized by the capacity for passage of air expressed in m^3/h, in accordance with the difference in pressures. This passage capacity referred to the total surface area of the window (passage capacity per unit of surface area, m^3/h m^2).

The air permeability of each of the windows was estimated in accordance with the classification of windows into four types established by the UNE-EN 12207:2000 standard (UNE, 2000) for a reference differential pressure of 100 hPa. It was considered that, without any additional treatment to enhance the permeability properties, PVC and aluminium windows with thermal break are classified in Class 4, whereas wooden and aluminium windows without break would be included in Class 3. This signifies permeability coefficients of 1.5 $m^3/h\ m^2$ for PVC and aluminium windows with break, whereas this coefficient increases to 7.0 $m^3/h\ m^2$ in scenarios involving wooden and aluminium windows without break.

4.5.4 Estimate of energy demand

For the three regions selected, the differences were calculated between the comfort temperature inside the room (22 °C) and the mean monthly temperatures. Positive differences indicate the need for heating, while negative differences signify the need for climatization.

The monthly electricity consumption values to raise or lower the inside temperature of the air (32.4 m^3) to 22 °C are estimated assuming that the air-conditioning system is switched on 24 times a month, and a value of 1,004.67 J $kg^{-1}\ °C^{-1}$ for the specific heat of the air. The electricity consumption values are determined for 5 hours of continuous use each time the appliances are switched on.

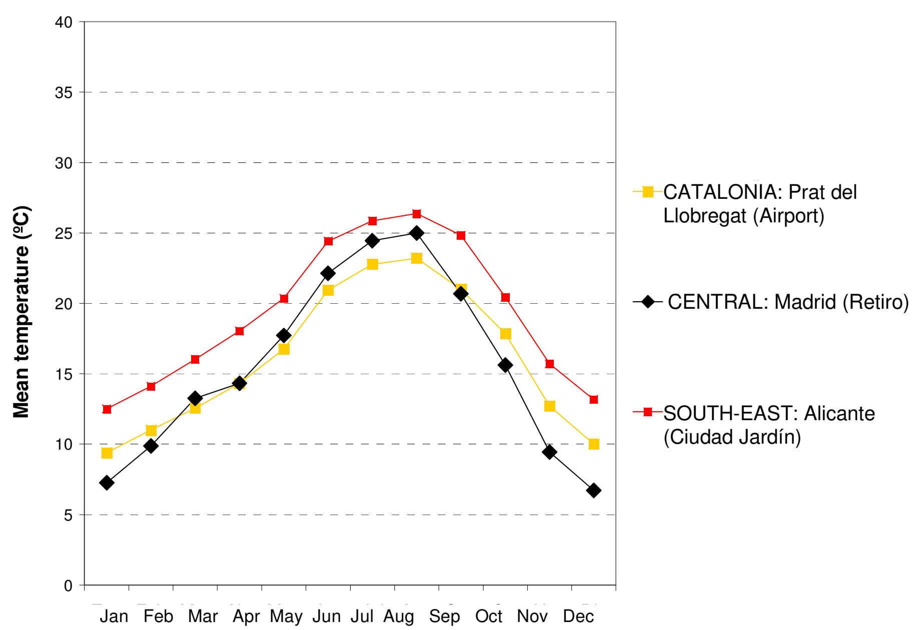

Figure 4.2: Monthly variation in the mean atmospheric temperatures in the three selected regions of Spain

The values obtained by scenario are set out in detail in Tables 4.5-4.9. Table 4.10 gives a summary of the annual electrical consumption figures for heating and climatization for each selected region and by type of window.

Table 4.5: Calculation of the annual electrical energy required for heating and climatization with a PVC window with double glazing ($U_{wall/window}$ = 0.65 W m^{-2} °C^{-1})

Month	Home	Exterior	Difference	Requirement	Electricity consumption kWh $month^{-1}$	Heat flow W	Heat loss kWh $month^{-1}$	Electrical consumption kWh $month^{-1}$	Loss through permeability kWh $month^{-1}$
				Catalonia – Prat de Llobregat (Airport)					
Jan	22	9.4	12.6	Heating	1.31	66.6	8.0	3.1	0.4
Feb	22	11.0	11.0	Heating	1.14	58.0	7.0	2.7	0.3
Mar	22	12.6	9.4	Heating	0.98	49.8	6.0	2.3	0.3
Apr	22	14.3	7.7	Heating	0.79	40.6	4.9	1.9	0.2
May	22	16.8	5.2	Heating	0.54	27.7	3.3	1.3	0.2
Jun	22	20.9	1.1	Heating	0.11	5.6	0.7	0.3	0.0
Jul	22	22.8	-0.8	Climatization	0.08	4.1	0.5	0.2	0.0
Aug	22	23.2	-1.2	Climatization	0.13	6.4	0.8	0.3	0.0
Sep	22	21.0	1.0	Heating	0.10	5.2	0.6	0.2	0.0
Oct	22	17.9	4.2	Heating	0.43	21.9	2.6	1.0	0.1
Nov	22	12.7	9.3	Heating	0.96	49.0	5.9	2.3	0.3
Dec	22	10.0	12.0	Heating	1.24	63.3	7.6	2.9	0.4
				Subtotals	7.8			18.4	2.4
							Total (kWh a^{-1})		**28.5**
				Madrid – Retiro					
Jan	22	7.3	14.8	Heating	1.53	77.9	9.3	3.6	0.5
Feb	22	9.9	12.1	Heating	1.25	64.0	7.7	3.0	0.4
Mar	22	13.3	8.8	Heating	0.91	46.2	5.5	2.1	0.3
Apr	22	14.3	7.7	Heating	0.80	40.6	4.9	1.9	0.2
May	22	17.7	4.3	Heating	0.44	22.6	2.7	1.0	0.1
Jun	22	22.1	-0.1	Climatization	0.01	0.7	0.1	0.0	0.0
Jul	22	24.4	-2.4	Climatization	0.25	12.9	1.5	0.6	0.1
Aug	22	25.0	-3.0	Climatization	0.31	15.8	1.9	0.7	0.1
Sep	22	20.7	1.3	Heating	0.14	7.0	0.8	0.3	0.0
Oct	22	15.6	6.4	Heating	0.66	33.7	4.0	1.6	0.2
Nov	22	9.4	12.6	Heating	1.30	66.4	8.0	3.1	0.4
Dec	22	6.7	15.3	Heating	1.58	80.7	9.7	3.7	0.5
				Subtotals	9.2			21.6	2.8
							Total (kWh a^{-1})		**33.6**
				Alicante – Ciudad Jardín					
Jan	22	12.5	9.5	Heating	0.98	50.1	6.0	2.3	0.3
Feb	22	14.1	7.9	Heating	0.82	41.7	5.0	1.9	0.2
Mar	22	16.0	6.0	Heating	0.62	31.6	3.8	1.5	0.2
Apr	22	18.0	4.0	Heating	0.41	20.9	2.5	1.0	0.1
May	22	20.4	1.7	Heating	0.17	8.7	1.0	0.4	0.1
Jun	22	24.4	-0.4	Climatization	0.04	2.2	0.3	0.1	0.0
Jul	22	25.9	-1.9	Climatization	0.19	9.8	1.2	0.5	0.1
Aug	22	26.4	-2.4	Climatization	0.25	12.6	1.5	0.6	0.1
Sep	22	24.8	-2.8	Climatization	0.29	15.0	1.8	0.7	0.1
Oct	22	20.4	1.6	Heating	0.16	8.3	1.0	0.4	0.0
Nov	22	15.7	6.3	Heating	0.65	33.2	4.0	1.5	0.2
Dec	22	13.2	8.8	Heating	0.91	46.6	5.6	2.2	0.3
				Subtotals	5.5			13.0	1.7
							Total (kWh a^{-1})		**20.1**

Table 4.6: Calculation of the annual electrical energy required for heating and climatization with an aluminium window without break and with double glazing ($U_{wall/window}$ = 0.89 W m^{-2} °C^{-1})

Month	Home	Exterior	Difference	Requirement	Electricity consumption kWh $month^{-1}$	Heat flow W	Heat loss kWh $month^{-1}$	Electrical consumption kWh $month^{-1}$	Loss through permeability kWh $month^{-1}$
				Catalonia – Prat de Llobregat (Airport)					
Jan	22	9.4	12.6	Heating	1.31	90.9	10.9	4.2	1.8
Feb	22	11.0	11.0	Heating	1.14	79.2	9.5	3.7	1.6
Mar	22	12.6	9.4	Heating	0.98	68.0	8.2	3.1	1.4
Apr	22	14.3	7.7	Heating	0.79	55.3	6.6	2.6	1.1
May	22	16.8	5.2	Heating	0.54	37.8	4.5	1.7	0.8
Jun	22	20.9	1.1	Heating	0.11	7.7	0.9	0.4	0.2
Jul	22	22.8	-0.8	Climatization	0.08	5.6	0.7	0.3	0.1
Aug	22	23.2	-1.2	Climatization	0.13	8.7	1.0	0.4	0.2
Sep	22	21.0	1.0	Heating	0.10	7.1	0.9	0.3	0.1
Oct	22	17.9	4.2	Heating	0.43	29.9	3.6	1.4	0.6
Nov	22	12.7	9.3	Heating	0.96	66.9	8.0	3.1	1.4
Dec	22	10.0	12.0	Heating	1.24	86.4	10.4	4.0	1.7
				Subtotals	7.8			25.1	11.0
								Total (kWh a^{-1})	**43.9**
				Madrid – Retiro					
Jan	22	7.3	14.8	Heating	1.53	106.3	12.8	4.9	2.2
Feb	22	9.9	12.1	Heating	1.25	87.4	10.5	4.0	1.8
Mar	22	13.3	8.8	Heating	0.91	63.0	7.6	2.9	1.3
Apr	22	14.3	7.7	Heating	0.80	55.4	6.6	2.6	1.1
May	22	17.7	4.3	Heating	0.44	30.9	3.7	1.4	0.6
Jun	22	22.1	-0.1	Climatization	0.01	1.0	0.1	0.0	0.0
Jul	22	24.4	-2.4	Climatization	0.25	17.6	2.1	0.8	0.4
Aug	22	25.0	-3.0	Climatization	0.31	21.6	2.6	1.0	0.4
Sep	22	20.7	1.3	Heating	0.14	9.5	1.1	0.4	0.2
Oct	22	15.6	6.4	Heating	0.66	46.0	5.5	2.1	0.9
Nov	22	9.4	12.6	Heating	1.30	90.5	10.9	4.2	1.8
Dec	22	6.7	15.3	Heating	1.58	110.1	13.2	5.1	2.2
				Subtotals	9.2			29.5	12.9
								Total (kWh a^{-1})	**51.6**
				Alicante – Ciudad Jardín					
Jan	22	12.5	9.5	Heating	0.98	68.4	8.2	3.2	1.4
Feb	22	14.1	7.9	Heating	0.82	56.9	6.8	2.6	1.2
Mar	22	16.0	6.0	Heating	0.62	43.1	5.2	2.0	0.9
Apr	22	18.0	4.0	Heating	0.41	28.6	3.4	1.3	0.6
May	22	20.4	1.7	Heating	0.17	11.9	1.4	0.5	0.2
Jun	22	24.4	-0.4	Climatization	0.04	2.9	0.4	0.1	0.1
Jul	22	25.9	-1.9	Climatization	0.19	13.4	1.6	0.6	0.3
Aug	22	26.4	-2.4	Climatization	0.25	17.2	2.1	0.8	0.3
Sep	22	24.8	-2.8	Climatization	0.29	20.5	2.5	0.9	0.4
Oct	22	20.4	1.6	Heating	0.16	11.3	1.4	0.5	0.2
Nov	22	15.7	6.3	Heating	0.65	45.3	5.4	2.1	0.9
Dec	22	13.2	8.8	Heating	0.91	63.6	7.6	2.9	1.3
				Subtotals	5.5			17.7	7.8
								Total (kWh a^{-1})	**30.9**

Table 4.7: Calculation of the annual electrical energy required for heating and climatization with an aluminium window with break and with double glazing ($U_{wall/window}$ = 0.77 W m^{-2} °C^{-1})

Month	Home	Exterior	Difference	Requirement	Electricity consumption kWh $month^{-1}$	Heat flow W	Heat loss kWh $month^{-1}$	Electrical consumption kWh $month^{-1}$	Loss through permeability kWh $month^{-1}$
				Catalonia – Prat de Llobregat (Airport)					
Jan	22	9.4	12.6	Heating	1.31	79.1	9.5	3.7	0.4
Feb	22	11.0	11.0	Heating	1.14	68.9	8.3	3.2	0.3
Mar	22	12.6	9.4	Heating	0.98	59.2	7.1	2.7	0.3
Apr	22	14.3	7.7	Heating	0.79	48.2	5.8	2.2	0.2
May	22	16.8	5.2	Heating	0.54	32.9	3.9	1.5	0.2
Jun	22	20.9	1.1	Heating	0.11	6.7	0.8	0.3	0.0
Jul	22	22.8	-0.8	Climatization	0.08	4.9	0.6	0.2	0.0
Aug	22	23.2	-1.2	Climatization	0.13	7.6	0.9	0.4	0.0
Sep	22	21.0	1.0	Heating	0.10	6.2	0.7	0.3	0.0
Oct	22	17.9	4.2	Heating	0.43	26.0	3.1	1.2	0.1
Nov	22	12.7	9.3	Heating	0.96	58.2	7.0	2.7	0.3
Dec	22	10.0	12.0	Heating	1.24	75.2	9.0	3.5	0.4
				Subtotals	7.8			21.8	2.4
							Total (kWh a^{-1})		**32.0**
				Madrid – Retiro					
Jan	22	7.3	14.8	Heating	1.53	92.5	11.1	4.3	0.5
Feb	22	9.9	12.1	Heating	1.25	76.1	9.1	3.5	0.4
Mar	22	13.3	8.8	Heating	0.91	54.9	6.6	2.5	0.3
Apr	22	14.3	7.7	Heating	0.80	48.2	5.8	2.2	0.2
May	22	17.7	4.3	Heating	0.44	26.9	3.2	1.2	0.1
Jun	22	22.1	-0.1	Climatization	0.01	0.8	0.1	0.0	0.0
Jul	22	24.4	-2.4	Climatization	0.25	15.3	1.8	0.7	0.1
Aug	22	25.0	-3.0	Climatization	0.31	18.8	2.3	0.9	0.1
Sep	22	20.7	1.3	Heating	0.14	8.3	1.0	0.4	0.0
Oct	22	15.6	6.4	Heating	0.66	40.0	4.8	1.8	0.2
Nov	22	9.4	12.6	Heating	1.30	78.8	9.5	3.6	0.4
Dec	22	6.7	15.3	Heating	1.58	95.9	11.5	4.4	0.5
				Subtotals	9.2			25.7	2.8
							Total (kWh a^{-1})		**37.6**
				Alicante – Ciudad Jardín					
Jan	22	12.5	9.5	Heating	0.98	59.5	7.1	2.7	0.3
Feb	22	14.1	7.9	Heating	0.82	49.5	5.9	2.3	0.2
Mar	22	16.0	6.0	Heating	0.62	37.5	4.5	1.7	0.2
Apr	22	18.0	4.0	Heating	0.41	24.9	3.0	1.1	0.1
May	22	20.4	1.7	Heating	0.17	10.3	1.2	0.5	0.1
Jun	22	24.4	-0.4	Climatization	0.04	2.6	0.3	0.1	0.0
Jul	22	25.9	-1.9	Climatization	0.19	11.7	1.4	0.5	0.1
Aug	22	26.4	-2.4	Climatization	0.25	14.9	1.8	0.7	0.1
Sep	22	24.8	-2.8	Climatization	0.29	17.8	2.1	0.8	0.1
Oct	22	20.4	1.6	Heating	0.16	9.9	1.2	0.5	0.0
Nov	22	15.7	6.3	Heating	0.65	39.5	4.7	1.8	0.2
Dec	22	13.2	8.8	Heating	0.91	55.4	6.6	2.6	0.3
				Subtotals	5.5			15.4	1.7
							Total (kWh a^{-1})		**22.6**

Table 4.8: Calculation of the annual electrical energy required for heating and climatization with a wooden window with double glazing ($U_{wall/window}$ = 0.68 W m^{-2} °C^{-1})

Month	Home	Exterior	Difference	Requirement	Electricity consumption kWh $month^{-1}$	Heat flow W	Heat loss kWh $month^{-1}$	Electrical consumption kWh $month^{-1}$	Loss through permeability kWh $month^{-1}$
Catalonia – Prat de Llobregat (Airport)									
Jan	22	9.4	12.6	Heating	1.31	69.7	8.4	3.2	1.8
Feb	22	11.0	11.0	Heating	1.14	60.8	7.3	2.8	1.6
Mar	22	12.6	9.4	Heating	0.98	52.2	6.3	2.4	1.4
Apr	22	14.3	7.7	Heating	0.79	42.5	5.1	2.0	1.1
May	22	16.8	5.2	Heating	0.54	29.0	3.5	1.3	0.8
Jun	22	20.9	1.1	Heating	0.11	5.9	0.7	0.3	0.2
Jul	22	22.8	-0.8	Climatization	0.08	4.3	0.5	0.2	0.1
Aug	22	23.2	-1.2	Climatization	0.13	6.7	0.8	0.3	0.2
Sep	22	21.0	1.0	Heating	0.10	5.5	0.7	0.3	0.1
Oct	22	17.9	4.2	Heating	0.43	22.9	2.8	1.1	0.6
Nov	22	12.7	9.3	Heating	0.96	51.3	6.2	2.4	1.4
Dec	22	10.0	12.0	Heating	1.24	66.3	8.0	3.1	1.7
				Subtotals	7.8			19.2	11.0
								Total (kWh a^{-1})	**38.1**
Madrid – Retiro									
Jan	22	7.3	14.8	Heating	1.53	81.5	9.8	3.8	2.2
Feb	22	9.9	12.1	Heating	1.25	67.0	8.0	3.1	1.8
Mar	22	13.3	8.8	Heating	0.91	48.4	5.8	2.2	1.3
Apr	22	14.3	7.7	Heating	0.80	42.5	5.1	2.0	1.1
May	22	17.7	4.3	Heating	0.44	23.7	2.8	1.1	0.6
Jun	22	22.1	-0.1	Climatization	0.01	0.7	0.1	0.0	0.0
Jul	22	24.4	-2.4	Climatization	0.25	13.5	1.6	0.6	0.4
Aug	22	25.0	-3.0	Climatization	0.31	16.5	2.0	0.8	0.4
Sep	22	20.7	1.3	Heating	0.14	7.3	0.9	0.3	0.2
Oct	22	15.6	6.4	Heating	0.66	35.3	4.2	1.6	0.9
Nov	22	9.4	12.6	Heating	1.30	69.5	8.3	3.2	1.8
Dec	22	6.7	15.3	Heating	1.58	84.5	10.1	3.9	2.2
				Subtotals	9.2			22.6	12.9
								Total (kWh a^{-1})	**44.8**
Alicante – Ciudad Jardín									
Jan	22	12.5	9.5	Heating	0.98	52.5	6.3	2.4	1.4
Feb	22	14.1	7.9	Heating	0.82	43.6	5.2	2.0	1.2
Mar	22	16.0	6.0	Heating	0.62	33.1	4.0	1.5	0.9
Apr	22	18.0	4.0	Heating	0.41	21.9	2.6	1.0	0.6
May	22	20.4	1.7	Heating	0.17	9.1	1.1	0.4	0.2
Jun	22	24.4	-0.4	Climatization	0.04	2.3	0.3	0.1	0.1
Jul	22	25.9	-1.9	Climatization	0.19	10.3	1.2	0.5	0.3
Aug	22	26.4	-2.4	Climatization	0.25	13.2	1.6	0.6	0.3
Sep	22	24.8	-2.8	Climatization	0.29	15.7	1.9	0.7	0.4
Oct	22	20.4	1.6	Heating	0.16	8.7	1.0	0.4	0.2
Nov	22	15.7	6.3	Heating	0.65	34.8	4.2	1.6	0.9
Dec	22	13.2	8.8	Heating	0.91	48.8	5.9	2.3	1.3
				Subtotals	5.5			13.6	7.8
								Total (kWh a^{-1})	**26.8**

Table 4.9: Calculation of the annual electrical energy required for heating and climatization with a wooden window with single glazing ($U_{wall/window}$ = 1.14 W m^{-2} °C^{-1})

Month	Home	Exterior	Difference	Requirement	Electricity consumption kWh month^{-1}	Heat flow W	Heat loss kWh month^{-1}	Electrical consumption kWh month^{-1}	Loss through permeability kWh month^{-1}
				Catalonia – Prat de Llobregat (Airport)					
Jan	22	9.4	12.6	Heating	1.31	116.2	13.9	5.4	1.8
Feb	22	11.0	11.0	Heating	1.14	101.3	12.2	4.7	1.6
Mar	22	12.6	9.4	Heating	0.98	87.0	10.4	4.0	1.4
Apr	22	14.3	7.7	Heating	0.79	70.8	8.5	3.3	1.1
May	22	16.8	5.2	Heating	0.54	48.3	5.8	2.2	0.8
Jun	22	20.9	1.1	Heating	0.11	9.8	1.2	0.5	0.2
Jul	22	22.8	-0.8	Climatization	0.08	7.1	0.9	0.3	0.1
Aug	22	23.2	-1.2	Climatization	0.13	11.2	1.3	0.5	0.2
Sep	22	21.0	1.0	Heating	0.10	9.1	1.1	0.4	0.1
Oct	22	17.9	4.2	Heating	0.43	38.3	4.6	1.8	0.6
Nov	22	12.7	9.3	Heating	0.96	85.6	10.3	3.9	1.4
Dec	22	10.0	12.0	Heating	1.24	110.5	13.3	5.1	1.7
				Subtotals	7.8			32.1	11.0
								Total (kWh a^{-1})	**50.9**
				Madrid – Retiro					
Jan	22	7.3	14.8	Heating	1.53	136.0	16.3	6.3	2.2
Feb	22	9.9	12.1	Heating	1.25	111.8	13.4	5.2	1.8
Mar	22	13.3	8.8	Heating	0.91	80.7	9.7	3.7	1.3
Apr	22	14.3	7.7	Heating	0.80	70.8	8.5	3.3	1.1
May	22	17.7	4.3	Heating	0.44	39.5	4.7	1.8	0.6
Jun	22	22.1	-0.1	Climatization	0.01	1.2	0.1	0.1	0.0
Jul	22	24.4	-2.4	Climatization	0.25	22.5	2.7	1.0	0.4
Aug	22	25.0	-3.0	Climatization	0.31	27.6	3.3	1.3	0.4
Sep	22	20.7	1.3	Heating	0.14	12.1	1.5	0.6	0.2
Oct	22	15.6	6.4	Heating	0.66	58.8	7.1	2.7	0.9
Nov	22	9.4	12.6	Heating	1.30	115.8	13.9	5.3	1.8
Dec	22	6.7	15.3	Heating	1.58	140.9	16.9	6.5	2.2
				Subtotals	9.2			37.7	12.9
								Total (kWh a^{-1})	**59.9**
				Alicante – Ciudad Jardín					
Jan	22	12.5	9.5	Heating	0.98	87.5	10.5	4.0	1.4
Feb	22	14.1	7.9	Heating	0.82	72.7	8.7	3.4	1.2
Mar	22	16.0	6.0	Heating	0.62	55.2	6.6	2.5	0.9
Apr	22	18.0	4.0	Heating	0.41	36.6	4.4	1.7	0.6
May	22	20.4	1.7	Heating	0.17	15.2	1.8	0.7	0.2
Jun	22	24.4	-0.4	Climatization	0.04	3.8	0.5	0.2	0.1
Jul	22	25.9	-1.9	Climatization	0.19	17.1	2.1	0.8	0.3
Aug	22	26.4	-2.4	Climatization	0.25	22.0	2.6	1.0	0.3
Sep	22	24.8	-2.8	Climatization	0.29	26.2	3.1	1.2	0.4
Oct	22	20.4	1.6	Heating	0.16	14.5	1.7	0.7	0.2
Nov	22	15.7	6.3	Heating	0.65	58.0	7.0	2.7	0.9
Dec	22	13.2	8.8	Heating	0.91	81.3	9.8	3.8	1.3
				Subtotals	5.5			22.6	7.8
								Total (kWh a^{-1})	**35.9**

The lowest annual electrical consumption values are for the region of Alicante (20.1 kWh a^{-1}, PVC window); whereas the highest values occur in Madrid (33.6 kWh a^{-1}, PVC window). Intermediate values occur in the region of Prat de Llobregat (28.5 kWh a^{-1}, PVC window).

Table 4.10 also includes the estimates of the annual CO_2 emissions, calculated by application of the emission factor of the Spanish electricity generation mix (0.443 kg CO_2 kWh^{-1}). In ascending order, for the PVC window, the estimated emissions are 9 kg CO_2 a^{-1} for Alicante, 13 kg CO_2 a^{-1} for Prat de Llobregat, and 15 kg CO_2 a^{-1} for Madrid.

To estimate the total consumption in the use stage of the windows, a general period of 50 years was used.

Table 4.10: Summary of the annual electrical energy consumption figures required for heating and climatization of the room subject to analysis

Region	Type of frame / window	Annual electrical consumption (kWh a^{-1})	CO_2 emission (kg a^{-1})
Prat de Llobregat, Barcelona	PVC with double glazing	28.5	13
	Aluminium with double glazing (without break)	43.9	19
	Aluminium with double glazing (with break)	32.0	14
	Wooden with double glazing	38.1	17
	Wooden with single glazing	50.9	23
Madrid	PVC with double glazing	33.6	15
	Aluminium with double glazing (without break)	51.6	23
	Aluminium with double glazing (with break)	37.6	17
	Wooden with double glazing	44.8	20
	Wooden with single glazing	59.9	27
Alicante	PVC with double glazing	20.1	9
	Aluminium with double glazing (without break)	30.9	14
	Aluminium with double glazing (with break)	22.6	10
	Wooden with double glazing	26.8	12
	Wooden with single glazing	35.9	16

4.6 Deconstruction

This activity, which consists of dismantling the window with the aim of making maximum use of the materials by recycling, may only require labour, and perhaps a minor energy consumption. It is assumed that the energy consumption in this stage is negligible.

4.7 Recycling

It is assumed that 97% of the PVC, aluminium and glass contained in the window is recyclable. The remaining 3% is made up of waste materials which are deposited in a disposal site. In the case of wood, it is considered that all of it is disposed of as waste.

To recycle the PVC frames, an electrical consumption of 0.25 kWh kg^{-1} is used (Asoven release).

To recycle aluminium, glass and steel, electrical consumption values of 4.17 kWh kg^{-1} (WBG, 2004), 2.03 kWh kg^{-1} (EPA, 2004) and 5.03 kWh kg^{-1} (EPA, 2004), respectively, are used. The values for glass and steel correspond to the energy consumption for smelting of primary glass and steel, as indicated by the respective European BREF documents.

4.8 Final disposal

An energy consumption of 0.155 kWh is assumed per kg of waste deposited in a disposal site (Choate and Ferland, 2004). It is considered that the energy is 100% diesel fuel.

4.9 Transport

It is assumed that the transport associated with the different stages of the life cycle is carried out in cargo trucks which use diesel fuel, and they have an energy demand of 0.00073 kWh km^{-1} kg^{-1} (WEC, 1998). This value is applicable to Western Europe.

A mean journey of 100 km was considered for the transport of materials to the assembly plant; and 100 km for both transport of the window to the site of installation and for disposal of the waste materials in a disposal site.

4.10 Emission factors

Table 4.11 presents the basic CO_2 emission factors used in each stage, according to the composition or type of energy supply as indicated above for each case.

Table 4.11: CO_2 emission factors

Energy / fuel source	Emission factor t C TJ^{-1} (IPCC, 1996)	t CO_2 TJ^{-1}	t CO_2 MWh^{-1}
Spanish electrical mix			0.443*
Production of PVC at Hispavic - Vinilis (Martorell)			0.284*¶
Diesel / fuel-oil	20.2	74.1	0.267
Natural gas	15.3	56.1	0.202
Coal	26.2	96.1	0.346

* Deducted in the document: "Estimate of the energy consumption and CO_2 emission associated with unit production of PVC, JM Baldasano &R. Parra. January 2005".
¶ Corresponds to the calculation criterion considering the objective of joint obtention of PVC and caustic soda.

5 Results and comparative analysis

5.1 Estimate of energy consumption and CO_2 emission figures for the wall/window system

The analysis of the results presented here includes the energy consumption and CO_2 emission figures obtained for the region of Prat de Llobregat (Barcelona), which are considered as representative values for Spain.

The highest energy usages in the stage of extraction and production of materials, in descending order, correspond to the aluminium window (1,407 kWh for windows with 30% recycled aluminium and 1,981 kWh if no recycled material is included); the PVC window (214 kWh and 254 kWh with 30% recycled PVC included and for windows without recycled PVC, respectively); the wooden window with double glazing (76 kWh) and the wooden window with single glazing (45 kWh), which presents the lowest energy consumption in the extraction and production stage, consequent to the use of just one pane of glass. This information is summarized in Table 5.1.

Table 5.1: Estimate of energy consumption and CO_2 emissions in the materials extraction and production stage; percentage of the total.

	Energy consumption		CO_2 emission	
	kWh	%	kg	%
Wooden window, single glazing	44.7	1.7	13.7	1.2
Wooden window, double glazing	74.5	3.6	22.2	2.5
PVC window, 30% recycled PVC	214.0	12.3	66.3	9.1
PVC window, 0% recycled PVC	253.6	14.2	77.6	10.5
Aluminium window, no break, 30% recycled Al	1,406.5	36.6	613.5	36.5
Aluminium window, with break, 30% recycled Al	1,406.5	43.4	613.5	43.3
Aluminium window, no break, 0% recycled Al	1,981.1	44.9	867.9	44.8
Aluminium window, with break, 0% recycled Al	1,981.1	51.9	867.9	51.9

Tables 5.2-5.9 summarize the information obtained for the different scenarios analysed. The energy consumption figures for the use stage refer to energy losses through the window. In every case, it is noted that this is the stage with the highest percentages. For PVC, aluminium and wooden windows, the percentages are 82%, 58% and 97%, respectively.

For PVC windows, the other components with the highest energy demand correspond to the stage of extraction and production of materials (14%) and the stage of recycling (5%). Using 30% recycled PVC in the manufacture of the PVC frames signifies a reduction in energy demand in the extraction and production stage, of 254 kWh to 214 kWh (a 16% reduction).

For aluminium windows, the energy consumption consequent to extraction and production of materials represents between 42 and 57% of the total energy used. Using 30% recycled aluminium signifies a reduction in energy demand in the extraction and production stage, of 1,981 kWh to 1.407 kWh (a 29% reduction). Consumption for recycling materials represents approximately 7% of total energy consumption.

Table 5.2: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for a PVC window with double glazing (without using recycled PVC in the frame, $U_{wall/window}$ = 0.65 W m^{-2} $°C^{-1}$). Summary

	Energy consumption		CO_2 emission	
	kWh	%	kg	%
Extraction and production	253.6	14.2	77.6	10.5
Transport to assembly	3.9	0.2	1.0	0.1
Assembly	4.8	0.3	2.1	0.3
Transport to building	3.9	0.2	1.0	0.1
Use (50 years)	1,427.4	80.2	632.1	85.2
Transport to disposal site	0.1	0.0	0.0	0.0
Disposal in disposal site	0.2	0.0	0.1	0.0
Transport to recycling	3.9	0.2	1.0	0.1
Recycling	82.2	4.6	26.6	3.6
Total:	1,780	100	742	100

Table 5.3: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for a PVC window with double glazing (using 30% recycled PVC in the frame, $U_{wall/window}$ = 0.65 W m^{-2} $°C^{-1}$). Summary

	Energy consumption		CO_2 emission	
	kWh	%	kg	%
Extraction and production	214.0	12.3	66.3	9.1
Transport to assembly	3.9	0.2	1.0	0.1
Assembly	4.8	0.3	2.1	0.3
Transport to building	3.9	0.2	1.0	0.1
Use (50 years)	1,427.4	82.0	632.1	86.6
Transport to disposal site	0.1	0.0	0.0	0.0
Disposal in disposal site	0.2	0.0	0.1	0.0
Transport to recycling	3.9	0.2	1.0	0.1
Recycling	82.2	4.7	26.6	3.6
Total:	1,740	100	730	100

Table 5.4: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for an aluminium window without break and with double glazing (without using recycled aluminium, $U_{wall/window}$ = 0.89 W m^{-2} °C^{-1}). Summary

	Energy consumption		CO_2 emission	
	kWh	%	kg	%
Extraction and production	1,981.1	44.9	867.9	44.8
Transport to assembly	4.8	0.1	1.3	0.1
Assembly	4.8	0.1	2.1	0.1
Transport to building	4.8	0.1	1.3	0.1
Use (50 years)	2,194.5	49.7	971.8	50.2
Transport to disposal site	0.1	0.0	0.0	0.0
Disposal in disposal site	0.3	0.0	0.1	0.0
Transport to recycling	4.8	0.1	1.3	0.1
Recycling	217.8	4.9	89.6	4.6
Total:	4,413	100	1,935	100

Table 5.5: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for an aluminium window without break and with double glazing (using 30% recycled aluminium, $U_{wall/window}$ = 0.89 W m^{-2} °C^{-1}). Summary

	Energy consumption		CO_2 emission	
	KWh	%	kg	%
Extraction and production	1,406.5	36.6	613.5	36.5
Transport to assembly	4.8	0.1	1.3	0.1
Assembly	4.8	0.1	2.1	0.1
Transport to building	4.8	0.1	1.3	0.1
Use (50 years)	2,194.5	57.2	971.8	57.8
Transport to disposal site	0.1	0.0	0.0	0.0
Disposal in disposal site	0.3	0.0	0.1	0.0
Transport to recycling	4.8	0.1	1.3	0.1
Recycling	217.8	5.7	89.6	5.3
Total:	3,838	100	1,681	100

Table 5.6: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for an aluminium window with break and with double glazing (without using recycled aluminium, $U_{wall/window}$ = 0.77 W m^{-2} °C^{-1}). Summary

	Energy consumption		CO_2 emission	
	kWh	%	kg	%
Extraction and production	1,981.1	51.9	867.9	51.9
Transport to assembly	4.8	0.1	1.3	0.1
Assembly	4.8	0.1	2.1	0.1
Transport to building	4.8	0.1	1.3	0.1
Use (50 years)	1,600.0	41.9	708.6	42.4
Transport to disposal site	0.1	0.0	0.0	0.0
Disposal in disposal site	0.3	0.0	0.1	0.0
Transport to recycling	4.8	0.1	1.3	0.1
Recycling	217.8	5.7	89.6	5.4
Total:	3,819	100	1,672	100

Table 5.7: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for an aluminium window with break and with double glazing (using 30% recycled aluminium, $U_{wall/window}$ = 0.77 W m^{-2} °C^{-1}). Summary

	Energy consumption		CO_2 emission	
	kWh	%	kg	%
Extraction and production	1,406.5	43.4	613.5	43.3
Transport to assembly	4.8	0.1	1.3	0.1
Assembly	4.8	0.1	2.1	0.1
Transport to building	4.8	0.1	1.3	0.1
Use (50 years)	1,600.0	49.3	708.6	50.0
Transport to disposal site	0.1	0.0	0.0	0.0
Disposal in disposal site	0.3	0.0	0.1	0.0
Transport to recycling	4.8	0.1	1.3	0.1
Recycling	217.8	6.7	89.6	6.3
Total:	3,244	100	1,418	100

Table 5.8: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for a wooden window with double glazing. ($U_{wall/window}$ = 0.68 W m^{-2} °C^{-1}). Summary

	Energy consumption		CO_2 emission	
	kWh	%	kg	%
Extraction and production	74.5	3.6	22.2	2.5
Transport to assembly	2.5	0.1	0.7	0.1
Assembly	4.8	0.2	2.1	0.2
Transport to building	2.5	0.1	0.7	0.1
Use (50 years)	1,906.8	93.2	844.4	95.3
Transport to disposal site	1.0	0.1	0.3	0.0
Disposal in disposal site	2.2	0.1	0.6	0.1
Transport to recycling	2.5	0.1	0.7	0.1
Recycling	47.9	2.3	14.4	1.6
Total:	2,045	100	886	100

Table 5.9: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for a wooden window with single glazing. ($U_{wall/window}$ = 1.14 W m^{-2} °C^{-1}). Summary

	Energy consumption		CO_2 emission	
	kWh	%	kg	%
Extraction and production	44.7	1.7	13.7	1.2
Transport to assembly	1.7	0.1	0.5	0.0
Assembly	4.8	0.2	2.1	0.2
Transport to building	1.7	0.1	0.5	0.0
Use (50 years)	2,548.9	96.8	1,128.8	97.7
Transport to disposal site	1.0	0.0	0.3	0.0
Disposal in disposal site	2.1	0.1	0.6	0.0
Transport to recycling	1.7	0.1	0.5	0.0
Recycling	26.2	1.0	8.2	0.7
Total:	2,633	100	1,155	100

Figures 5.1-5.6 present, by stages and in graphic form, the estimates for energy consumption and CO_2 emissions for each type of window analysed.

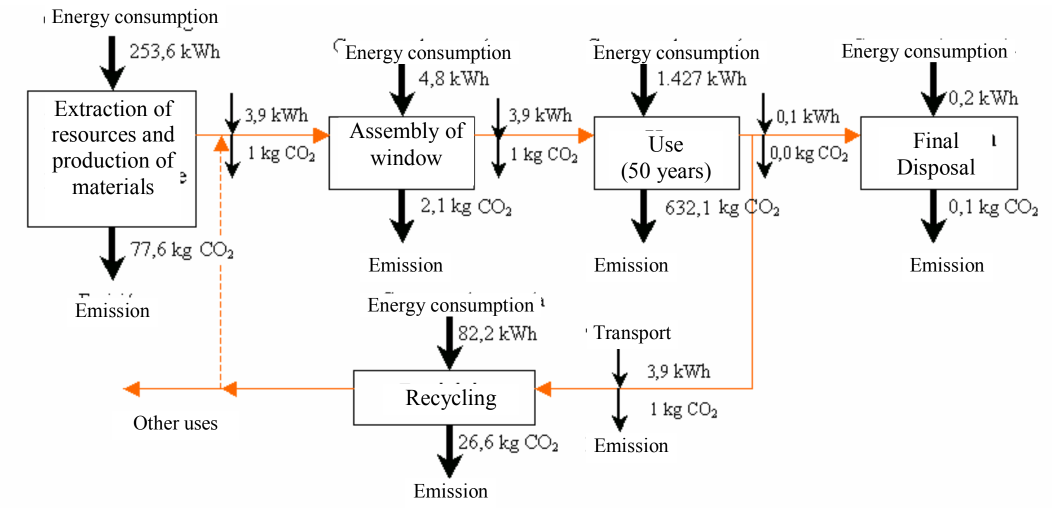

Figure 5.1: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for a PVC window with double glazing (without using recycled PVC in the window structure)

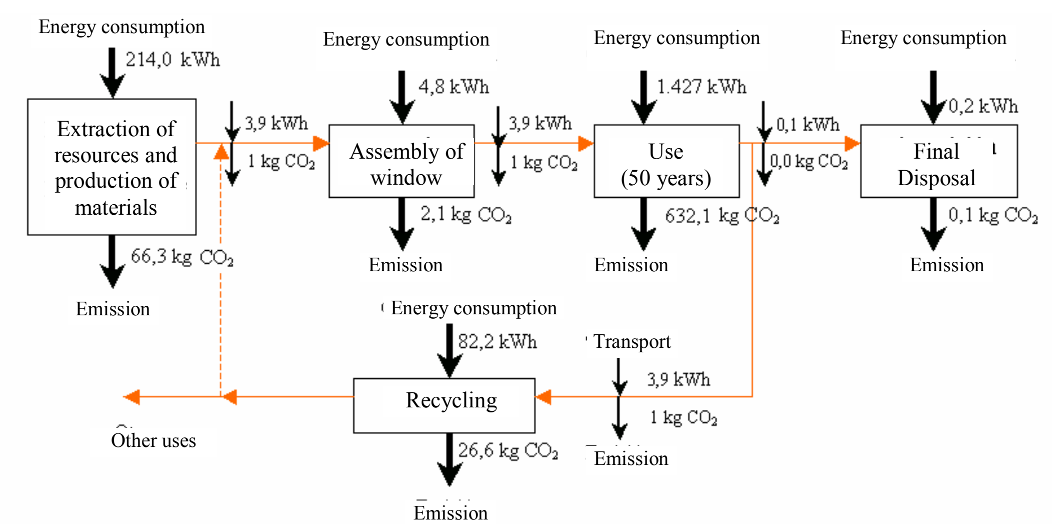

Figure 5.2: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for a PVC window with double glazing (using 30% recycled PVC in the window structure)

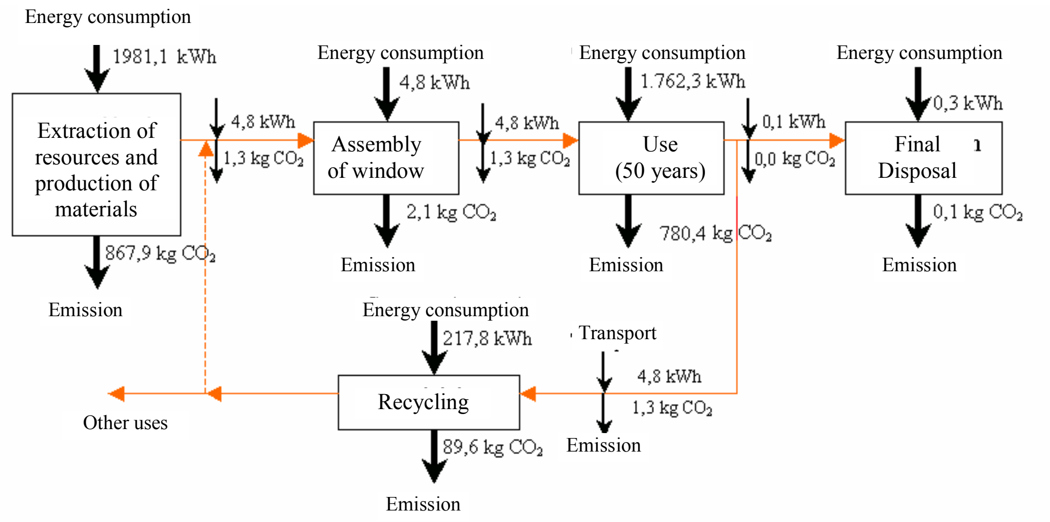

Figure 5.3: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for an aluminium window without break and with double glazing (without using recycled aluminium in the window structure)

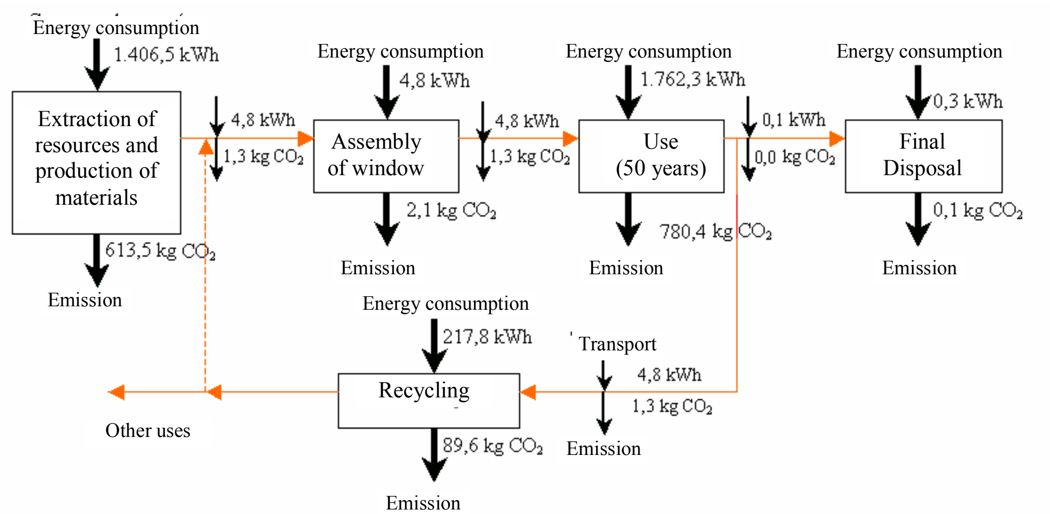

Figure 5.4: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for an aluminium window without break and with double glazing (using 30% recycled aluminium in the window structure)

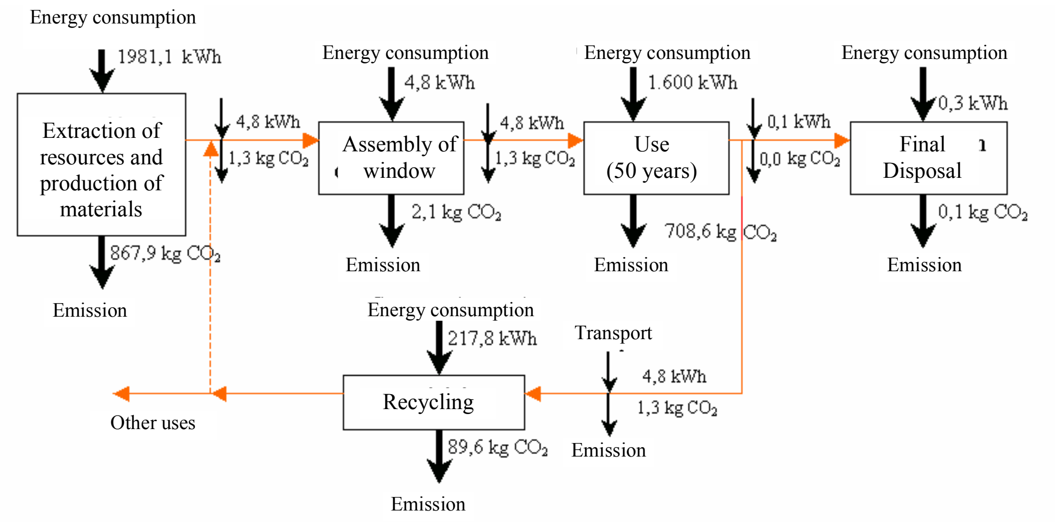

Figure 5.5: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for an aluminium window with break and with double glazing (without using recycled aluminium in the window structure)

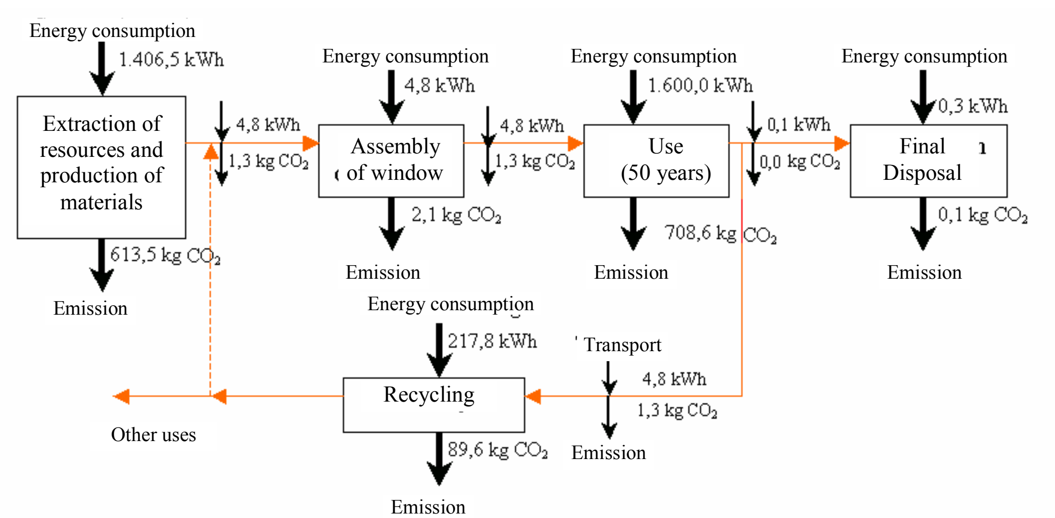

Figure 5.6: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for an aluminium window with break and with double glazing (using 30% recycled aluminium in the window structure)

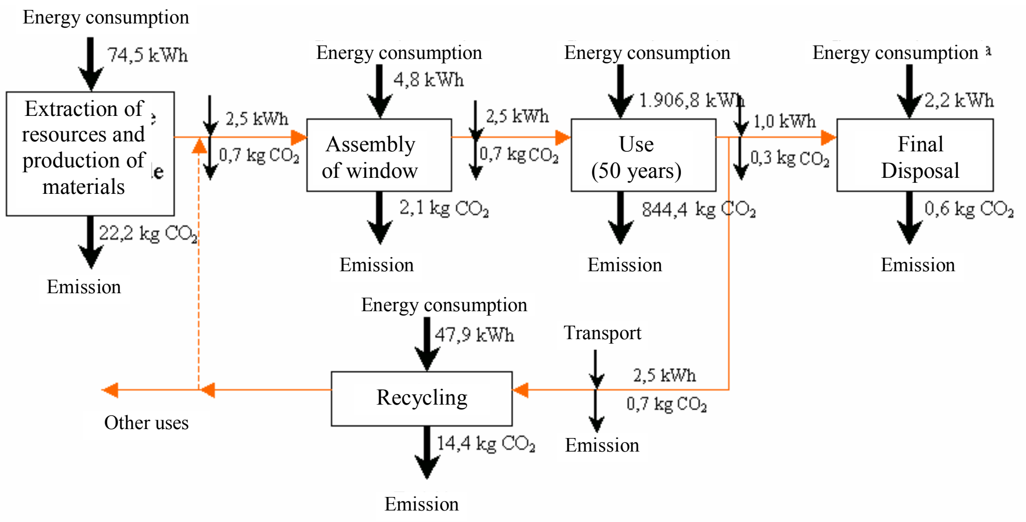

Figure 5.7: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for a wooden window with double glazing

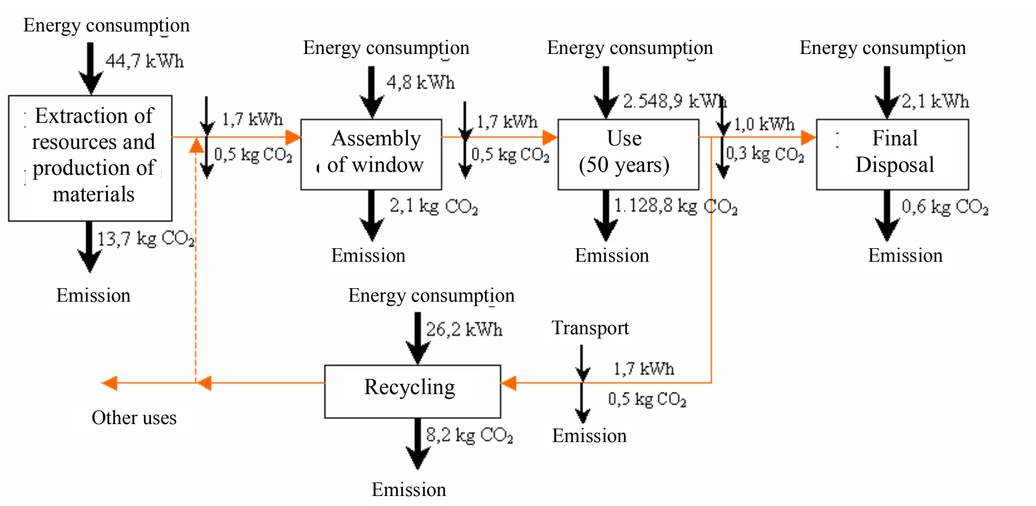

Figure 5.8: Estimate of energy consumption and CO_2 emissions consequent to the production, use, recycling and final disposal of waste materials for a wooden window with single glazing

Table 5.10 presents a summary of overall energy consumption figures and the respective CO_2 emissions, for the 8 cases analysed. It also includes the weight of recycled material.

Table 5.10: Summary of the figures for energy consumption, CO_2 emission and recycled material attributable to the production, use (50 years), recycling and final disposal of waste materials for windows manufactured from different materials.

Window	Electrical consumption (kWh)	CO_2 emissions (kg)	Recycled material (kg)					
			Glass	PVC	Steel	Aluminium	Total material recycled	% of total material
30% recycled PVC with double glazing	1,740	730	21.4	21.1	6.7		49.2	93.4%
0% recycled PVC with double glazing	1,780	742	21.4	21.1	6.7		49.2	93.4%
Wooden with double glazing	2,045	886	21.4				21.4	61.5%
Wooden with single glazing	2,633	1,155	10.7				10.7	45.0%
30% recycled aluminium *with break* and double glazing	3,244	1,418	21.4			40.8	62.2	94.1%
0% recycled aluminium *with break* and double glazing	3,819	1,672	21.4			40.8	62.2	94.1%
30% recycled aluminium *without break* and double glazing	3,838	1,681	21.4			40.8	62.2	94.1%
0% recycled aluminium *without break* and double glazing	4,413	1,935	21.4			40.8	62.2	94.1%

The PVC window with 30% recycled material presents the lowest energy consumption (1,740 kWh) and CO_2 emissions (730 kg). At the end of the recycling stage, 21.4 kg of secondary glass, 21.1 kg of PVC and 6.7 of steel are obtained, making a total of 49.2 kg recycled material (93.4% of the total material of the window). The PVC window without recycled material presents energy consumption of 1,780 kWh and CO_2 emission of 742 kg. The total quantity of recycled materials also amounts to 49.2 kg (93.4%).

The wooden window with double glazing presents energy consumption of 2,045 kWh and CO_2 emissions of 886 kg. In the recycling stage, the 21.4 kg of glass (61.5% of the material of the window) are reusable. Next comes the wooden window with single glazing. This window presents the highest thermal conductivity coefficient ($U_{wall/window}$ 1.14 W m^{-2} $°C^{-1}$), although lower energy consumption in the materials extraction and production stage signifies that in the overall results, this window presents lower energy consumption (2,549 kWh) and CO_2 emissions (1,129 kg CO_2) than those obtained for the aluminium windows, but higher than for the PVC window. This window provides the least amount of recycled material (10.7 kg of glass; 45.0%).

The highest values of energy used and CO_2 emissions correspond to the aluminium windows. The windows with 30% recycled aluminium present an energy consumption of 3,244 kWh and 3,838 kWh for windows with and without thermal break. These windows present CO_2 emissions of 1,418 kg and 1,681 kg, respectively. For windows which do not use recycled aluminium, the energy consumption figures are 3,819 kWh and 4,413 kWh for windows with and without thermal break, in that order (CO_2 emissions of 1,672 kg for the window with thermal break, and 1,935 kg for the aluminium window without thermal break). All the aluminium windows provide 62.2 kg of recycled material (94.1% of the total material of the window).

6 Conclusions

This document sets out the estimates of energy consumption and CO_2 emissions associated with the production, use, recycling and final disposal of waste materials attributable to a standard casement window measuring 1.34 m x 1.34 m, with double glazing, the structural frames of which are manufactured alternatively in PVC, aluminium (with and without thermal break) and wood. Given that wooden windows with single glazing are widely used in Spain, this alternative has been included as an eighth case of complementary analysis.

The focus encompasses all the stages of a Life Cycle Assessment Analysis, although it only analyses the two environmental factors indicated above; and it aims for the results to be representative for the Iberian Peninsula, both as regards consumption figures and configuration of the energy sources. Priority has therefore been given to the information for this region; however, the analysis is complemented with information in the sphere of Europe and internationally.

The basic data used in this document include the CO_2 emission factor of the electrical mix in Spain for 2002, and the respective values for energy consumption and CO_2 emissions associated with the production of PVC, taking the PVC plant located in Martorell as a reference.

In order to estimate the impact of the energy consumption and carbon dioxide emissions, a methodology for environmental accounting of these indicators has been devised, consisting of estimating their value in each of the stages of the life cycle of a window (extraction and production, transport to assembly, assembly, transport to building, use, transport to disposal site, disposal in disposal site, transport to recycling and recycling). The end results signify the equivalent sum of the energy consumption and CO_2 emission figures for each of these stages.

The values for energy consumption in assembly of the PVC windows and recycling correspond to reliable information, provided by the producers themselves. In this respect, we would highlight the lesser reliability of the energy consumption values used for other materials such as aluminium, glass and wood, where European and international data have been used. The variability of the results does not affect the use stage which, as we have seen, forms the stage of greatest energy demand and, therefore, of highest CO_2 emissions.

The window attributed the least energy consumption and CO_2 emission is the PVC window with 30% recycled material, followed by the PVC window without recycled material. The highest values of energy used and CO_2 emissions correspond to the aluminium windows with no recycled material and without thermal break.

The results obtained indicate that, in all the cases analysed, the highest percentages of energy consumption correspond to the window's use stage. The energy consumption figures in the stages of extraction and production of materials are considerable (up to 52% of the total value) for aluminium windows. This percentage is lower for PVC (14%) and wooden (4%) windows.

The lighter weight of PVC benefits the transport costs of this material in comparison with other, heavier materials, such as aluminium.

With regard to recycling the window materials, in the cases of PVC and aluminium there is greater availability of recycled material for manufacture of a new window, or for these materials to be used in other products. In the case of wooden windows, as the material cannot be recycled, new wood has to be extracted and treated.

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