Energy consumptions and CO_2 emissions resulting from different handling strategies of glass from end-of-life vehicles.

Master of Science Thesis

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Abstract

Every year a large number of vehicles become useless. They become end-of-life vehicles (ELV) and need to be scrapped. The materials from a vehicle will be taken care of for reuse, recycling, recovery or disposal. For the glass, there are at least three scenarios, with different handling techniques:

1. dismantling of the glass from the ELV before the ELV is shredded
2. separation of the glass, from the shredder waste, to be used for new glass products, or
3. separation of the glass along with some other inorganic fractions, from the shredder waste, to be used for filling material

The purpose of this study is to investigate and compare the environmental impacts from these three scenarios. The investigation is from a life-cycle perspective, beginning when the ELV arrives at the vehicle dismantler and ending when the glass has become a new product. The glass is not a hazardous material and all emissions to the environment are directly linked to the use of energy, with one exception. When new glass products are produced from virgin materials, some chemically bound carbon is released as CO_2, which will be prevented if recycled glass is used instead. All results are therefore presented as energy consumptions and CO_2 emissions.

The recycling of glass results in small reductions in energy consumptions and CO_2 emissions, compared with recycling of other materials. In this study, scenario 1 presents itself with a higher possible recycling rate and also the highest savings of energy and CO_2. Scenario 2 has the second highest savings and a brighter future in technical development within the recycling business. The simplest option presented in this study is scenario 3, with savings close to zero.

Definitions and abbreviations

ASR	‘auto shredder residue’ is the leftover material that remains after the shredding of vehicles and recovering of metals. The ASR may still contain a variety of metals that are not recoverable with traditional methods.
CO_2	‘carbon dioxide’ is a greenhouse gas.
ELV	’end-of-life vehicle’ means a vehicle which is waste.
EU-25	is defined as the 25 Member States of the European Union from 1 May 2004 (Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden and the United Kingdom).
insurance case	is a vehicle that has become waste prematurely, e.g. due to an accident or infestation.
LCA	’life cycle assessment’ is a method to evaluate the environmental impact from the complete life cycle of a product, process or activity.
recovery	means to reprocess waste materials in a production process for the original purpose or for other purposes, including energy recovery.
recycling	means to reprocess waste materials in a production process for the original purpose or for other purposes, excluding energy recovery.
reuse	means any operation by which components are used for the same purpose for which they were created.

Contents

1 Introduction

The number of cars existing in the world is great and it increases all the time. All these cars will eventually need to be taken care of as waste or “end-of-life vehicles” (ELVs) as they are called. In Sweden alone, 288,881 cars were scrapped during 2006 [1].

In September 2000 the European Commission set up goals for the reuse, recycling and recovery of ELVs in Europe. Article 7.2 from the ELV Directive [2] tells us that:

> *Member States shall take the necessary measures to ensure that the following targets are attained by economic operators:*
> *no later than 1 January* ***2006****, for all end-of life vehicles, the* ***reuse and recovery*** *shall be increased to a minimum of* ***85 %*** *by an average weight per vehicle and year. Within the same time limit the* ***reuse and recycling*** *shall be increased to a minimum of* ***80 %*** *by an average weight per vehicle and year;*
> […]
> *no later than 1 January* ***2015****, for all end-of life vehicles, the* ***reuse and recovery*** *shall be increased to a minimum of* ***95 %*** *by an average weight per vehicle and year. Within the same time limit, the* ***reuse and recycling*** *shall be increased to a minimum of* ***85 %*** *by an average weight per vehicle and year.*

Annex I of the ELV Directive [2] gives us some “minimum technical requirements for treatment [...]”, where subsection 4 describes the “treatment operations in order to promote recycling”:

> *removal of catalysts,*
> *removal of metal components containing copper, aluminium and magnesium* ***if these metals are not segregated in the shredding process****,*
> *removal of tyres and large plastic components (bumpers, dashboard, fluid containers, etc),* ***if these materials are not segregated in the shredding process*** *in such a way that they can be effectively recycled as materials,*
> ***removal of glass.***

Some of the EU-member states have implemented exceptions to some of these requirements. As an example, the Danish Environment Agency can allow shredders to accept ELVs “even if the glass or the plastic bumpers and spoilers are not removed in advance, provided that the enterprise can deliver proof demonstrating that glass and plastics are separated during the fragmentation process in such a way that recycling as material is possible”[1] [3] . The Swedish Environment Agency, on the other hand, say that the glass should be removed before any further treatment (e.g. shredding) may be performed [4].

The glass in itself is not hazardous, in contrast to some of the parts that should be removed according to Annex I.3[2] of the ELV directive, e.g. batteries, different fluids and components containing mercury [2]. The main component of flat glass is silicon dioxide (sand) which is an abundant raw material. Sodium oxide and calcium oxide are also used, sometimes together with small parts of magnesium oxide and aluminium oxide and perhaps some trace amounts of colour additives or similar [5–7]. None of these raw materials are considered to be scarce, in contrast to the metals used in e.g. the catalyst. Some energy can be saved by using recycled glass instead of virgin materials when manufacturing different glass products. Compared to

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[1] Directly translated from Danish, by Henric Lassesson.

[2] Treatment operations for depollution of end-of-life vehicles

other materials, e.g. steel and aluminium, the energy savings from recycled glass are quite small, see Figure 17.

Hence, the question emerged, if the best option really is to remove the glass from the ELV before the shredding process. This study investigates and compares the environmental impact of treating the glass in one of three different ways;

1. dismantling of the glass from the ELV before the ELV is shredded
2. separation of the glass, from the shredder waste, to be used for new glass products, or
3. separation of the glass along with some other inorganic fractions (e.g. ceramics, sand and metal oxides), from the shredder waste, to be used for filling material (e.g. in landfill, asphalt and concrete)

To be able to find an answer, it is necessary to calculate the total environmental impact of the glass. It is necessary to add up all parts of the life cycle, from the point when it arrives at the dismantler until it is a new product. It is also important to use a representative estimator when comparing the three scenarios.

The representative estimator used in this study is the consumption of energy and the emissions of CO_2. The energy consumption is divided into fossil fuels and electricity, where the fossil fuels are used for direct combustion in the process. Fossil fuels used for the electricity production are not included in the energy consumption. However, emissions of CO_2 from the electricity production are included. The use of energy in different forms plays the dominant role in environmental impacts in this analysis. The only other impact possible to find during this study was the release of chemically bound CO_2 from the melt when producing glass from virgin materials. As stated above, the glass is not a toxic material and the raw materials are not scarce. That is why no other emissions are included in this study. No account has been taken for the use of land (e.g. landfills) or the consumption of resources and raw materials, except for the energy use and CO_2 emissions when extracting and upgrading the raw material.

2 Methodology

This study is based on an LCA methodology, where the total environmental impact from the “cradle-to-grave” is calculated. The “cradle” in this case is when the ELV arrives at the dismantling centre and the “grave” is when the glass has become a new product. All activities before the dismantling centre is assumed to be the same in all scenarios and is therefore not included in the comparison.

The calculations are based on the basic flow diagram described in Figure 1. The energy consumptions and CO_2 emissions at every stage have been calculated and summed. For the reuse stage, however, no calculations have been made since it has been assumed to be the same for all three scenarios.

2.1 Data collection

The basis for data collection has been the open literature and online databases in an effort to get an overall view of how the ELVs and especially the glass from ELVs are handled today. This also may give an insight in how they might be handled in a near future and what level of energy consumptions and CO_2 emissions that are related to these handling techniques.

As later described in section 3, most of the glass is today dismantled from the ELV before the ELV is shredded. When an ELV gets shredded and all recyclable materials are separated, a fraction called auto-shredder residue (ASR) remains. Any glass, which is left in the ELV when it arrives at the shredder, will end up among the ASR. Some new techniques are able to separate a clean fraction of glass after the shredding. The glass that is separated after the shredding or dismantled before the shredding will need further cleaning before it can be recycled into new glass products. The glass that is not dismantled or separated usually ends up in an inorganic fraction of ASR, which is used as a construction material at landfills.

A few reports [8–11] discuss possibilities of new techniques for handling of the ASR. These reports usually focus on how to handle the organic part of the residues. Some literature about the recycling of glass was found [12], but unfortunately it only considered container glass.

In order to get a better picture of what really happens, some study visits were carried out. These were focussed on the dismantling stage [13, 14] and the shredding stage [15]. Otherwise interviews [15–30], mostly phone interviews, had to be used to get information about energy consumption and effectiveness of different stages.

It was in some cases not possible to find the required information. In these cases estimations have been made. These estimations are described in section 3 and further investigated in section 5. Most of the information is based on site-specific data, describing a plausible scenario for an ELV left for dismantling in southern Sweden.

2.2 Calculations

Several specialized software exist for life-cycle assessment (LCA) calculations (e.g. SimaPro and GaBi). Due to the simplicity of the calculations, it was decided to use MatLab and Excel instead.

2.3 Goal

The main goal of this study is to compare the difference in environmental impacts from different handling strategies of ELV glazing. To shed some light on what is the environmentally best available technology for treating the glass and how big the difference can be between the different options.

2.4 Scope

The chosen product is the glass from an average ELV in Sweden sometime around today (2007-2008). In the first scenario the glass is treated according to an approximation of what is happening in Sweden today, with the ELV directive in place. In the second scenario, the ELV is shredded with all of the glass left inside, followed by a separation of the glass with the technology that is available today. In the third scenario, the ELV is shredded with all of the glass left inside, and the glass is treated in the same way as glass residue left in the ELV is treated as today, i.e. used as a construction material at landfills.

2.4.1 Functional unit

For a fair comparison between the three scenarios, a common functional unit is needed. In this study we will use 1 kg glass passing through the “dismantler” stage.

2.4.2 Choice of impact categories and method for impact assessment

Early in this study it was noticed that most of the environmental impacts were due to energy consumptions. In fact, the only other type of environmental impact we could find was the release of chemically bound CO_2 when glass is produced from virgin materials. With an environmental analysis, studying all environmental impacts, the results can vary quite a lot depending on what type of energy being used. The amount of energy being used will, on the other hand, probably not change that much. The differences are primarily between electric energy and thermal (fossil) energy. The electric energy is a secondary energy converted from a mix of other energies, e.g. hydro, wind, nuclear, oil, gas and coal. The thermal energy is directly used for heat, or mechanical movement from combustion engines. In this study all of the thermal energy derives from fossil fuels. Since most of the information is based on site-specific data, not average data, we decided to keep it simple and focus on the energy consumptions from the different scenarios. We also decided to include the CO_2 emissions, because of the extra emissions not caused by energy consumptions.

2.4.3 System boundaries

The life cycle of a product is normally considered to start at the manufacturing stage and end at the waste handling stage. However, since this study is a comparison between different ways of handling the waste, all stages prior to the waste handling have been excluded and the rest have been broken down to smaller pieces. In this study everything starts when the glass arrives at the dismantler and it ends after the recycling stage, i.e. when the glass has become a new product. Figure 1 illustrates the possible flows of glass in this study.

The reuse of glass from ELVs is not included in this study, since it is assumed to be the same in all scenarios and thereby not interesting for a comparison. It has also been assumed to be a relatively small amount of glass from ELVs that goes into the reuse stage. Most of the reused glass is dismantled from insurance cases, since these cars are not that old when they arrive at the dismantlers [13, 14]. The spare parts from an insurance case are more up-to-date with the car fleet of today. Approximately 10-15 % of the scrapped cars today are insurance cases [24] and handled differently due to the higher possibility to find spare parts, e.g. windshields and side windows. Hence, these insurance cases are not included in this study. If a window breaks during a cars life time, before it becomes an ELV, it will need to be replaced. Since this happens before it arrives at the dismantler and presumably happens in the same way in all our scenarios, it will also not be included in this study.

The geographical boundary is said to be within Sweden, meaning that the ELV arrives at a dismantler somewhere in Sweden. Later stages of the life cycle may be located elsewhere, inside or outside Sweden.

Only technologies that are in use today have been accounted for, except for the recycling which is based on research made in 1991 [12]. It is assumed that the difference in energy consumption, between making container glass from recycled glass and making container glass from virgin material, is similar today to what it was in 1991.

Scenario 2 will, compared to scenario 1 and 3, need some extra capital investments in the form of extra sorting machines in the shredding and sorting stage. Scenario 3 will need a bit less capital investment, compared to scenario 1 and 2, in the form of glass recycling facilities in the recycling stage. The production and maintenance of this extra (scenario 2) or unneeded (scenario 3) capital investments are not included in the study. The energy consumption from these capital investments, however, is included.

3 Inventory analysis

The studied object is glass that, along with the rest of the ELV, arrives at a vehicle dismantler in Sweden. It can follow any of the routes described in the basic flow diagram as it is illustrated in Figure 1.

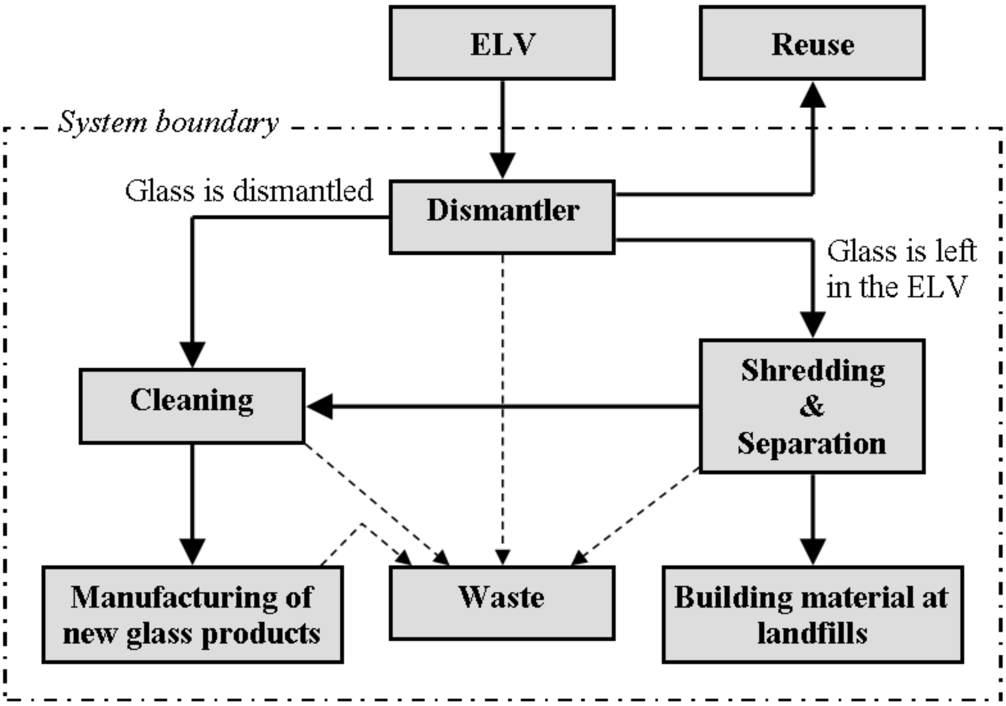

Figure 1: Simple flow chart, describing the possible routes for glass from ELV.

At the dismantler, the glass can be dismantled for reuse or recycling, or simply be left in the ELV. Any glass, which is left in the ELV, will be sent to the shredder along with the rest of the vehicle. At the shredder, the glass is today sorted into a fraction of inert materials, along with e.g. ceramics, sand and metal oxides. This fraction of inert materials is used as a construction material at landfills. Some new techniques are able to separate a clean fraction of glass after the shredding and send it to recycling. All glass sent for recycling will need further cleaning before it is used as raw material in the manufacturing of new glass products. In all of these stages a small amount of glass can become waste. Transports are needed between all stages.

We have divided the energy into fossil fuel and electricity, where the fossil fuels are diesel and oil, which are used for different kinds of direct combustion. The CO_2 emissions from electricity are based on a European (EU-25) average, since different stages of the life cycle are located in different parts of Europe (e.g. shredding in Sweden, cleaning in Germany and manufacturing of new glass products in Denmark).

3.1 Incoming flow = glass from the ELV

In 2004, the amount of glass and plastics in the most common Swedish car models of the years 1986-89 was examined [21]. Those cars were a major part of what became ELVs in 2004. The study showed that an average Swedish car from 1986-89 contains 29.4 kg glass in the form of 10.2 kg windshield, 12.4 kg side windows and 6.8 kg rear window. The headlights and possibility of a sunroof is not included in those figures. A study of Belgian ELVs [6] suggests that we add 2.0 kg of glass, in the form of 1.1 kg headlights and 0.9 kg sunroof. That gives us a total of 31 kg of glass in an average Swedish car before it becomes an ELV.

3.2 Dismantler

When the vehicle has become waste, it is (or at least should be) handed over to a dismantler. This is the first stage of our study. Everything that happens prior to this stage is assumed to be the same in all scenarios.

At the dismantler the ELV is treated for de-pollution, e.g. batteries, different fluids and components containing mercury are removed and air bags are removed or neutralized. Some parts of the ELV are reusable and are therefore dismantled in such a way that they can be sold on the second-hand market. The reusable parts are primarily removed from younger vehicles that have become waste because of a collision or similar, so-called insurance cases. The ELV is also treated for recycling, e.g. catalysts and sometimes tyres and plastic and metal components are removed.

This study focuses on the glass only. In Sweden today, the glass is also removed at the dismantler. It should be safe to assume that none of the other dismantling processes, mentioned above, will be affected if the glass is not removed, especially since the glass is sometimes the last part to be removed before the vehicle is compressed and sent to the shredder [13, 14].

3.2.1 Bildelcentrum Partille [13]

About 900-1000 cars per year are dismantled at Bildelcentrum Partille, but it is mostly insurance cases. Those cars that arrive at Bildelcentrum with intact windows keep their windows somewhat intact until shortly before they are compressed. The side windows from insurance cases are attractive on the second-hand market, since so many cars lose their side windows because of break-ins and thrashing. Otherwise, a tray is put under the car, the side windows are broken by force and the glass that falls into the tray is collected for recycling. The rear window is also broken by force, using a tarpaulin inside the car to collect the glass. If the windshield is glued on to the car it is possible to cut it out by hand. If the windshield is directly bonded to the body, hand force is no longer enough. Instead, an electric cutter is used. Some windows are already broken when they arrive at the dismantler, and those windows stay in the car. The headlights are only removed if they are possible to sell on the second hand market.

All of the collected glass is stored in one container before it is sent by truck to Swede Glass United in Askersund. The glass is only transported when a truck happens to be close to Partille and heading back to Askersund, thereby reducing the distance run by empty trucks. Glass transports go from Bildelcentrum ones every 1-1.5 years. The last transport, before the study visit, was 9.3 tonnes of glass, which corresponds to a fully loaded truck.

Bildelcentrum Partille compresses all the cars, with its own compressor. This is not the case in many other places, where it is standard to use a portable compressor transported to and from the dismantler by truck. After compression, the cars are stacked on top of each other for approximately one week before they are sent to the shredder. The trucks go to Stena Recycling’s shredding facility in Halmstad, with 17-20 compressed cars at a time. If they did not have to dismantle the glass, it would be sent together with (inside) the compressed cars to the shredder.

3.2.2 Uffes Bildelar, Orust [14]

A couple of thousand cars get dismantled every year at Uffes Bildelar, but none of them are insurance cases. Before any of the windows are dismantled, the car needs to be moved 40 m by a forklift to a big concrete plate. While it is on the plate, the side windows are broken by force and then swept up and put into a small container. Any visible stones or other impurities are picked out by hand. The rear window is also broken by force, using a tarpaulin inside the car to collect the glass, or it is cut out by hand if that is possible. While the windshield is still intact, the car is again moved 40 meters by forklift to the compressor. Most parts of the windshield come loose during the compression. The rest is possible to loosen by using hand force and a spade. After the compression and the eventual extra loosening, the windshield is lifted into the container with the use of simple hand force and the spade. Almost all cars have intact windows when they arrive at Uffes Bildelar and they stay intact until shortly before the compression.

The windshields, with laminated glass, are put into a different container than the glass from the side and rear windows, with hardened non-laminated glass. The small containers with glass are transported on the same trucks as the compressed cars, to Stena Recycling’s shredding facility in Halmstad.

It usually takes 1-2 weeks before the compressed cars are sent away and it is always the latest cars that are sent first. That means that some of the cars are sent the same day as they were compressed, others can stay out in the open for a very long time before they are sent away. While the compressed cars are waiting to be transported, there can be some leakage of oils and other liquids, caused by the rain. Even if the glass had not been dismantled, it would still be broken at this point, so the leakage would most likely be the same no matter if the glass is dismantled or not. There is a plan to put up a roof over the compressed cars, to reduce the leakage.

3.2.3 Data

Since it was impossible to visit or interview all dismantlers in Sweden, some assumptions and estimates had to be made. It is assumed that 70 % of the dismantlers use a forklift to transport the car 2×40 m in order to dismantle some glass parts, in the same way as they do at Uffes Bildelar. It is also assumed that 70 % of all dismantlers use an electric cutter to dismantle those windshields that are directly bonded to the body, in the same way as they do at Bildelcentrum Partille. In the car park of today, we approximate that 50 % of the windshields are directly bonded to the body.

If today’s dismantling processes are used, it is practically impossible to dismantle all the glass from a vehicle. The cutting and the breaking of a window always leave some parts behind, the headlights are usually left behind and some parts are already broken before they arrive at the dismantler. In a previous study [6] it is estimated that 60 to 85 % of the glass can be dismantled from a vehicle. Experiences from this study say that 60 to 90 % can be dismantled, with 80 % as a plausible estimation. The Swedish car dismantlers are not obliged to report how much glass they send to materials recycling before the year of 2008, which is too late for this report. Some dismantlers did report glass for recycling during 2007, with a total of 1,041,200 kg of glass. The same dismantlers also reported a total weight of chassis corresponding to 110,000 cars. This equals to 9.5 kg of glass per car or that just over 30 % of the glass is dismantled [25]. There are big differences in these numbers, which are analysed more thoroughly in section 5 Sensitivity analysis.

The electric cutter is estimated to need 1 kW of power during 2 minutes every time it is used to remove a windshield. According to Toyota [18], a forklift capable of doing the 2×40 m transport of an ELV would be a 3.5-5.0 ton forklift with a diesel engine and a consumption of 4.7 litres per hour. It is also estimated that this job would take 2-2.5 minutes to perform with this forklift, which corresponds to almost 0.2 litres of diesel per ELV.

3.3 Reuse

Some, still functioning, parts of a car are dismantled for reuse and that includes glass parts, especially side windows and headlights from newer cars. This is a quite small part of the total glass today and it is not expected to change in the three different scenarios. Hence it is not included in this study.

3.4 Shredding and separation

The ELV is usually compressed before it arrives at the shredder, unless the transport distance between the dismantler and shredder is very short, i.e. less than 50-70 km [16]. When the ELV arrives at the shredder it is usually stored for a while before the actual shredding begins.

3.4.1 Stena Recycling’s shredding facility in Halmstad [15]

Approximately 220,000 tonnes of scrap is handled every year, of which 30 % are cars, 30 % are industrial scrap, 30 % are municipal scrap and 10 % are others or unknown. Today, there is no separation between the incoming fractions. The cars are shredded along with the rest of the scrap.

The scrap is transported into an on-site storage before the shredding begins. A hammer mill tears the scrap into smaller pieces. A lighter fraction is sorted out through a big fan. The ferromagnetic metals (e.g. iron) are sorted out with electro magnets and the non-ferromagnetic metals (e.g. aluminium) are sorted out with eddy-current separators. After a few steps of washing and floatation the organics (e.g. plastics, rubber and wood) are also sorted out. What is left is a fraction that consists of minerals (i.e. glass, stones, gravel and sand) and other residue. This fraction is today used as a construction material at landfills. It is estimated that most of the glass that comes through the shredder ends up in this fraction.

3.4.2 H.J. Hansen [22]

The Danish Environmental Agency can accept that the glass is not dismantled, provided that H.J. Hansen can prove that they can separate the glass in the fragmentation process. The demand is today that 19 kg of glass need to be separated from a car that enters the fragmentation process with all of the glass left.

It is usually a mixture of scrap running through the process, but it is also needed to run some tests with nothing but scrapped cars, with all of the glass still remaining in the car when the process begins. During the last two of these tests, a portion of 18.7 and 21.2 kg glass per car, respectively, where separated. That was glass with less than 5 % impurities. Practically, not so much glass is separated, rather 5 kg per car with 40-50 % impurities. It is due to several factors; especially that glass is lost along the way, both before and after the car arrives at the shredder. Some cars arrive at the dismantler with parts of the glazing missing, some glass is lost during compression of the car, some is lost during transportation, some is lost while the car is lifted into the mill and some cars actually have their windows dismantled before they arrive at H.J. Hansen.

Optical sensors and pressurised air is used for the separation. The optical sensors recognise fragments of glass that are 3-4 mm or larger and when the glass fragments pass by a row of thrust nozzles the pressurised air is used to put the glass into a separate container.

3.4.3 Data

A modern Swedish shredding facility uses 15-20 kWh per ton input. This input consists of approximately 70 % iron. Approximately 90 % of the energy consumption originates from the hammer mill and the other 10 % from conveyor belts, magnets, sieves and other parts of the separation process. Since the iron is much harder to tear apart than most of the other materials that comes through the shredder, the iron is usually considered to be the only contributing part to the energy consumption. In other words; an extra amount of glass is usually considered to have no contributing effect on the energy consumption [29].

In the scenarios of shredding and separation similar to what is happening in Sweden today (scenario 1 and 3) we have in this study assumed an energy consumption of 2 kWh per ton of glass entering the shredder. This is assumed to be what a modern Swedish shredding facility will consume if the hammer mill is excluded.

In the scenario with a more advanced sorting (scenario 2) the same facility is used, with an addition of an optical sorting system that separates the glass with pressurized air. Based on experience [29, 30] from separation of different metals with a similar system, it is said that the pressurized air consumes most of the energy in this part of the process. The energy consumption seems to vary with several factors, e.g. shape and size of the separated particles and purity of the separated fraction. Based on examples from separating metals with this technique [29, 30], we have assumed an energy consumption of 125 kWh per ton of glass entering this optical sorting. The separation rate is assumed to be 65 %, which is just over 20 kg from an ELV containing 31 kg glass. This is based on the test runs from H.J. Hansen, with 18.7 and 21.2 kg glass per car.

3.5 Cleaning

When the glass has been removed from the rest of the ELV, either by dismantling or separation, it needs to be purified before it can be recycled as new glass products.

3.5.1 Stena Recycling’s shredding facility in Malmö [20]

Stena Recycling, Malmö, made an attempt to purify the glass from some Swedish car dismantlers, with an ambition to sell it as raw material for production of insulating fibre glass. The attempt was not a success, due to too high amounts of organics, so the process has stopped. The glass was not sorted as laminated and non-laminated before the process. A sorting like that would give a possibility to a higher purity in the end.

In this process the glass was crushed and separated by size. The smaller sizes were mainly glass and the larger sizes had a larger part laminating foil, since the foil does not get crushed so easily. Impurities in the form of aluminium, iron, wood and rubber were easy to remove with magnets, eddy-current separators and floatation.

During Stena Recycling’s attempt there was an input of 1190 tonnes and an output of 1097 tonnes. The output is described in Table 1. The process took 17.22 h and used 4281 kWh of electricity for the mill and the input. The conveyor and sieve are not included in the energy consumption.

Table 1: The output from one of Stena Recycling's attempts to purify glass from ELV [20].

Output	Weight [kg]	Description
Al	2.7	Sent for aluminium recycling
< 7 mm	436	Almost pure glass. Was supposed to be used as a raw material for manufacturing of glass fibre for insulation.
7-30 mm	587	70-75 % glass, the rest was laminating foil. Was sent for further purification of the glass, for glass recycling.
> 30 mm	71	80-90 % laminating foil, the rest was glass. Was sent to recycling of laminating foil.
TOTAL	**1097**	

3.5.2 Bernhard Reiling Glas Recycling GmbH [23]

Reiling has five recycling plants that totally process 500,000-550,000 tonnes of glass every year, 60,000-80,000 tonnes of which is windshield glass. Today, they do not take any car glass that has been separated after shredding, only dismantled and a big part from the windshield making industry. The rejected windshields from the industry are easier to handle since they have a more well known chemical composition.

In the processing of the windshields from cars, the first thing to do is to remove the laminating foil. This is done by crushing the glass and letting the humidity in the atmosphere react with the foil in such a way that the foil starts curling and loosens from the glass. The glass is then put into a hammer mill, after which the foil gets sucked out. When the foil has been removed, the glass is processed in the same way as all other types of glass to remove impurities in the form of metals and ceramics.

While shredding the windshields, Reiling has a throughput of ca. 30 tons per hour. The shredder consumes ca. 40 litre diesel per hour and a wheel loader uses ca. 14 litre diesel per hour. The electric power needed for conveyors etc. is ca. 15 kW.

While the glass is treated in the recycling line, to remove the impurities, Reiling has a throughput of 8 tons per hour. One wheel loader is used for 10 minutes per hour, with a consumption of 14 litre of diesel per hour. The overall energy consumption of the recycling line is unknown. The overall cost (incl. compressed air, current etc.) is ca. 8 €/hour.

These two steps of processing windshields results in an output of glass, impurities and laminating foil, as described in Table 2.

Table 2: The output from Reiling's cleaning of windshields.

Output	Yield	Description
glass	60-70 %	Finished (cleaned) glass, ready for usage in glass furnace.
impurities	ca. 10 %	Rejected impurities (metals, rubber of the sealing, etc.), sent to landfill and metal recycling.
laminating foil	20-30 %	Rejected lamination foil, dependent on the amount of non-laminated glass (pre-stressed safety glass) in the car glass. It is sent to landfill or PVB-recycling.

The finished glas has a good and constant quality, following Reilings specifications of less than 7 ppm of metals, less than 20 ppm of ceramics (incl stones) and less than 0.2 % organics. Some customers (buyers of the processed glass) have higher demands for the purity (e.g. < 10 ppm ceramics) and the chemical composition of the glass. Other customers have lower demands (e.g. up to 1000 ppm ceramics). With a high purity and a high certainty of the composition, the glass is wanted in the glass bottling industry. It was even mentioned that, when making bottles, the car glass can have a higher value than other glass, if the composition is well known, but it is only possible to make coloured glass, e.g. wine bottles. If the composition is unknown or fluctuating, or if the purity is low, the glass usually ends up as fibre glass for insulation. Less than 0.5 % of the processed glass is rejected. The rejected glass is then reprocessed.

3.5.3 Data

The Bernhard Reiling facility for windshields is used as a base case. This is a working facility that is used today. Swedish dismantlers do not have to separate the glass into laminated and non-laminated fractions. Hence we assume that all ELV glass, in scenario 1, goes through the full process. Due to lack of information of other processes we also assume the same process for scenario 2 as in scenario 1.

Step one uses 40 litres plus 14 litres of diesel per 30 tons of glass, for the shredder and the wheel loader. The electric power needed for conveyors etc. is ca. 15 kWh per 30 tons. In step two a wheel loader consumes 2.33 litres of diesel per 8 tons of glass (14 litres per hour and used for 10 minutes equals 2.33 litres). Step two is also assumed to need approximately 48 kWh per 8 tons of glass, based on the overall cost of 8 €/h and an electricity price of 0.1654 €/kWh [31] for German industries with a maximum demand of 500 kW. The full cost of 8 €/h is assumed to be from electricity.

Approximately 65 % (60-70 %) of the input is glass and the rest is laminating foil and impurities. In other words, for 1 kg of glass a total input of 1/0.65=1.54 kg is needed. All of this adds up to a consumption of 0.0032 litre diesel (0.11 MJ) and 0.010 kWh (0.036 MJ) per kg glass passing through the cleaning process. All of the glass that enters the cleaning process is assumed to go to materials recycling afterwards. The further handling (possibly recycling) of other materials than glass is not included in this study.

3.6 Manufacturing of new glass products

A variety of options exist when it comes to recycling the glass. It is not possible to use it in the production of new flat glass, because of too much impurities and an uncertainty in the chemical composition of the glass. A small amount of ELV glass can be used in the production of container glass (e.g. bottles). This is illustrated by the fact that Swede Glass United, one of the largest dealers in Swedish ELV glass, exports the glass to Italy where it becomes wine bottles [17]. The Italian customer is unknown due to trade secrets. A big part of the glass becomes fibre glass for insulation, a process described in section 3.6.1. It is also possible to use the glass in the production of foam glass.

3.6.1 Isover

In Isover's process of making glass wool, approximately 60 % of recycled glass is added [32]. This reduces the use of virgin materials and the need for energy in the process of extracting and transporting these virgin materials. Unfortunately, we do not know the amount of different virgin materials that will be reduced. In the process today, the virgin materials consist of 43 % sand, 3 % lime, 19 % soda and 34 % process additives [32]. Due to confidentially issues, we do not know what it would consist of if no recycled glass were added and we do not know what type of process additives that are being used.

It is estimated a 0.3 % decrease in the required melting energy for every additional 1 % of recycled glass (26). The melting energy is today 0.802 kWh per kg molten glass and consists of 100 % electricity [32]. We assume that 1 kg of raw material corresponds to 1 kg of molten glass, which is not completely true due to losses of water vapour and carbon dioxide. These losses are assumed to be small. We also assume that the 0.3 % decrease in required melting energy is based on the melting energy used today; with ca. 60 % recycled glass. That gives an energy saving of approximately 0.24 kWh (or 0.87 MJ) per added kg of recycled glass. No other energy savings are accounted for.

Isover use different types of recycled glass (e.g. ELV glass, flat glass and container glass) in their production. If the input of ELV glass decreases, Isover will try to increase the input of other types of recycled glass to compensate. If that is not possible, Isover will increase the input of virgin material. As a final option, the output will have to decrease [26].

3.6.2 Data

Isover will primarily try to compensate an eventual decrease of ELV glass with an increase of some other recycled glass. Hence, it is possible to assume that the increased use of virgin material will instead take place in a plant that produces container glass. Based on the market for recycled glass, other options are possible. Those options are handled in section 5 Sensitivity analysis.

We were able to make some calculations based on material balance and energy requirements from a previous study of container glass [12] combined with energy consumptions from different transports [12, 33]. Assuming that ELV glass is equal to container glass, the energy savings would be 0.84 MJ of electric energy and 1.96 MJ of fossil energy per kg of recycled glass added to the process. The extraction and transportation of raw material would in this case represent 89 % (0.75 MJ) of the electric energy and 52 % (1.02 MJ) of the fossil energy. The rest are energy savings from the melting process. An extra decrease in CO_2 emissions is obtained due to chemically bound carbon from the virgin material, e.g. soda and lime, which would otherwise be emitted from the melt. These emissions are ca. 170 g of CO_2 per kg of virgin material [12].

3.7 Construction material at landfills

In Sweden today, the glass that goes through a shredding and sorting facility usually ends up in a fraction of compact, non-combustible material. This material is used at landfills, as a construction material.

3.7.1 Data

In this step, 1 kg of glass will most likely substitute 1 kg of sand. We use the same information about extracting and transporting sand as we did when we calculated the impact from manufacturing of new glass products [12, 33]. An estimation of 0.10 MJ of electric energy per kg of glass will be saved in this step.

3.8 Waste

There will be a small amount of waste in more or less all stages. We have, as a base case, assumed that all glass waste can be used as a construction material at landfills. Hence, the amount of waste is zero. Other cases are discussed in section 5.

Since glass has no calorific value, there is no purpose in sending it to a waste incineration plant. The waste will be disposed of in landfills.

3.8.1 Data

A small amount of energy is used to take care of the landfill, 0.000684 MJ of electricity and 0.035 MJ of diesel per kg of waste [12]. Since the glass is an inert waste, there will be no extra pollutions to air or water.

3.9 Transports

The material needs to be transported between the different stages. There are big differences in transports, depending on where the ELV is dismantled and who the final buyer of the glass is. It is therefore important to use a similar route in all three scenarios, to make a fair comparison. The two major handlers in glass from ELVs are Stena Recycling and Swede Glass United.

Weight and volume are two limiting factors when it comes to transports. When the material is dense, the truck will never carry more than a maximum weight even if there is some empty space left. With a lighter material, the truck will fill up to a maximum volume even if the maximum weight has not been reached. When the glass is transported separately, the weight will always be the limiting factor. It is harder to say what the limiting factor is when the compressed ELVs are transported. Some of our sources say weight [13, 27, 28] and some of them say volume [15, 28], but all of them say that the limiting factor is close to being both weight and volume at the same time. A truck filled to a maximum volume of compressed ELVs is close to its maximum weight as well. A compressed ELV contains plenty of empty spaces where the glass can end up, i.e. some extra glass will only increase the weight, not the volume.

3.9.1 Stena Recycling

Stena Recycling has three options for their glass. The glass from northern Sweden is sent to Norway, probably to become foam glass. The glass from middle Sweden is sent to Otterbäcken, where it is taken care of by Swede Glass United. The glass from southern Sweden is sent to Malmö. Since the attempt of purifying the glass in Malmö was unsuccessful, the glass is now sent on to Reiling in Marienfeld, Germany. The approximate transport between an average dismantler and Malmö or Otterbäcken is 150 km by truck [19].

Reiling has different buyers for the purified glass, depending on the purity and certainty of the chemical composition [23]. A likely buyer for ELV glass is Isover in Vamdrup, Denmark.

3.9.2 Swede Glass United

All glass is directly delivered to the harbour in Otterbäcken, where Swede Glass United has a large storage. On average, the glass needs a 200 km truck transport to reach Otterbäcken. The glass is then transported by boat to northern Italy and 15 km by truck to its final destination [17].

3.9.3 Data

Instead of estimating average transports for the three different scenarios, we assume that the ELV is dismantled at the same location in all scenarios, ca. 150 km from Malmö. We assume that Reiling, at Marienfeld, purifies the glass in scenarios 1 and 2. We also assume that the final buyer is Isover in scenarios 1 and 2 and that the final destination is a local landfill in scenario 3. All transports are made by truck (diesel).

From the dismantler to the cleaning, the glass is transported on a separate truck, 150 km to Malmö plus 634 km to Marienfeld. Some of the glass might be transported in a separate container on the same truck as the compressed ELVs to Malmö. Since the separate container is an increase in volume, we assume that both cases will have the same effect.

From the dismantler to the shredding and sorting in Malmö, the glass is transported 150 km with the compressed ELVs. We assume that 50 % of the transports are limited by weight and 50 % are limited by volume, i.e. the average glass will only need 75 km of transport.

After the shredding and sorting, the transports are limited by weight. In scenario 1 and 3 it is transported to a local landfill, assumed to be 15 km away. In scenario 2 it is transported 634 km to Marienfeld.

The purified glass is transported 523 km from Marienfeld to Vamdrup.

All waste is transported to landfills, assumed to be 15 km away.

4 Results

The main result of this study is that recycling of ELV glass will, with the assumptions made, decrease the need for energy and the emissions of CO_2 to the atmosphere. The amount of glass that ends up as new glass products has a greater significance than what route it takes to get there. Negative numbers illustrates reductions in energy consumptions and CO_2 emissions.

4.1 Scenario 1

The first scenario illustrates what is happening in Sweden today. The glass needs to be dismantled before the ELV arrives at the shredder. The dismantled glass is cleaned before it is used as a raw material in the manufacturing of new glass products. All the glass that is left in the ELV arrives at the shredder and is later used as construction material at landfills. It is a bit uncertain how much glass that actually gets dismantled. A plausible flow diagram is illustrated in Figure 2 with an estimation of 80 % dismantling and 20 % left in the ELV. The energy consumptions and CO_2 emissions are divided into different stages and illustrated in Table 3, Figure 3 and Figure 4.

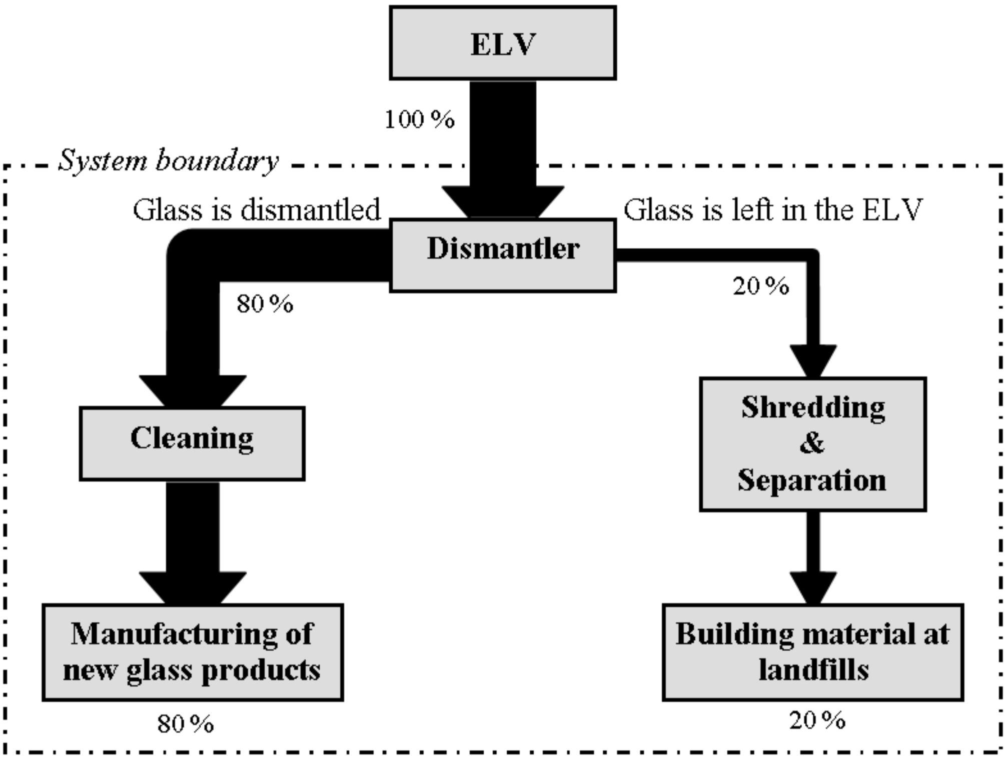

Figure 2: Flow diagram, describing the material flow, of scenario 1.

Table 3: Energy consumptions and CO_2 emissions for one kg of glass entering scenario 1.

Stage	fossil energy [MJ]	electric energy [MJ]	total energy [MJ]	CO_2 emissions [g]
(1) Total transports	0.691		0.691	49.99
(2) Dismantler	0.140	0.001	0.141	11.14
(3) Shredding & Separation		0.001	0.001	0.17
(4) Cleaning	0.090	0.029	0.119	10.43
(5) New glass products	-1.567	-0.672	-2.239	-365.41
(6) Construction material		-0.020	-0.020	-2.27
TOTAL	**-0.646**	**-0.660**	**-1.305**	**-295.96**

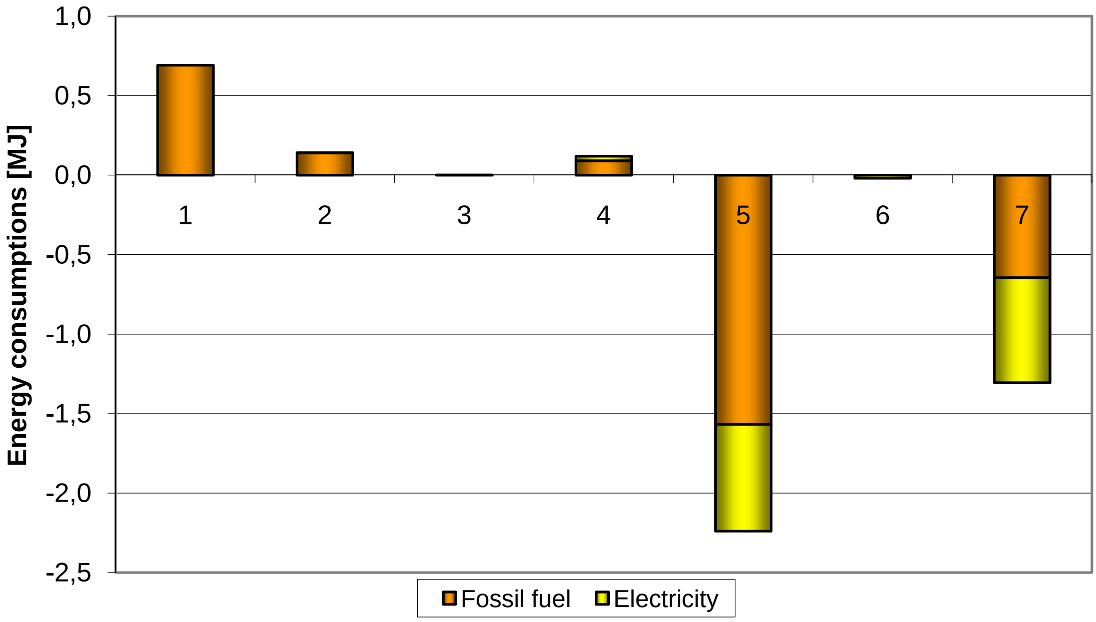

Figure 3: Energy consumptions for scenario 1. (1) Transports, (2) Dismantling, (3) Shredding & Separation, (4) Cleaning, (5) New glass products, (6) Construction material, (7) Total.

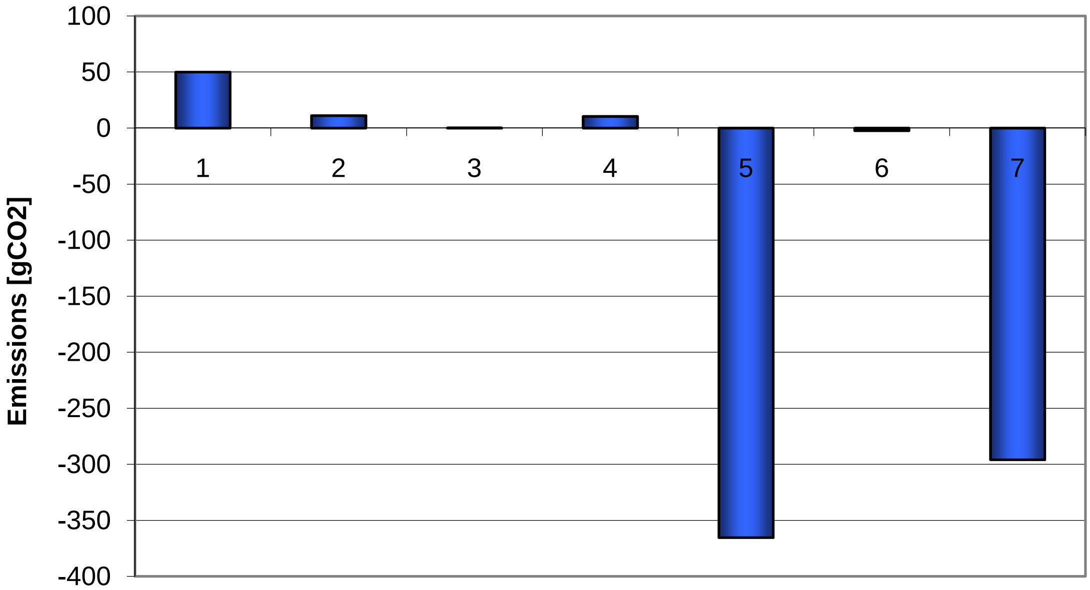

Figure 4: CO_2 emissions from scenario 1. (1) Transports, (2) Dismantling, (3) Shredding & Separation, (4) Cleaning, (5) New glass products, (6) Construction material, (7) Total.

With a dismantling of 80 % of the glass from an ELV we get a total reduction of 1.3 MJ and 300 gCO_2 per kg of glass. The greatest impact is here from the production of new glass products, caused by a reduced need in virgin material and a lower melting energy. The CO_2 savings from production of new glass products is not only from lower energy consumptions, but also from chemically bound carbon in the virgin material. The second greatest impact is from the transports, going by truck from Sweden to Germany to Denmark.

4.2 Scenario 2

The second scenario illustrates a possible scenario, similar to what is allowed in Denmark today, based on technology that is available today. The glass is not dismantled. Instead it is left in the ELV and separated after the shredding. The separated glass is cleaned before it is used as a raw material in the manufacturing of new glass products. A portion of the glass is not possible to separate and is instead used as construction material at landfills. Based on Danish legislation and tests done by H.J. Hansen we assume that 65 % of the glass is separated in this scenario. The flow diagram is illustrated in Figure 5. The energy consumptions and CO_2 emissions are divided into different stages and illustrated in Table 4, Figure 6 and Figure 7.

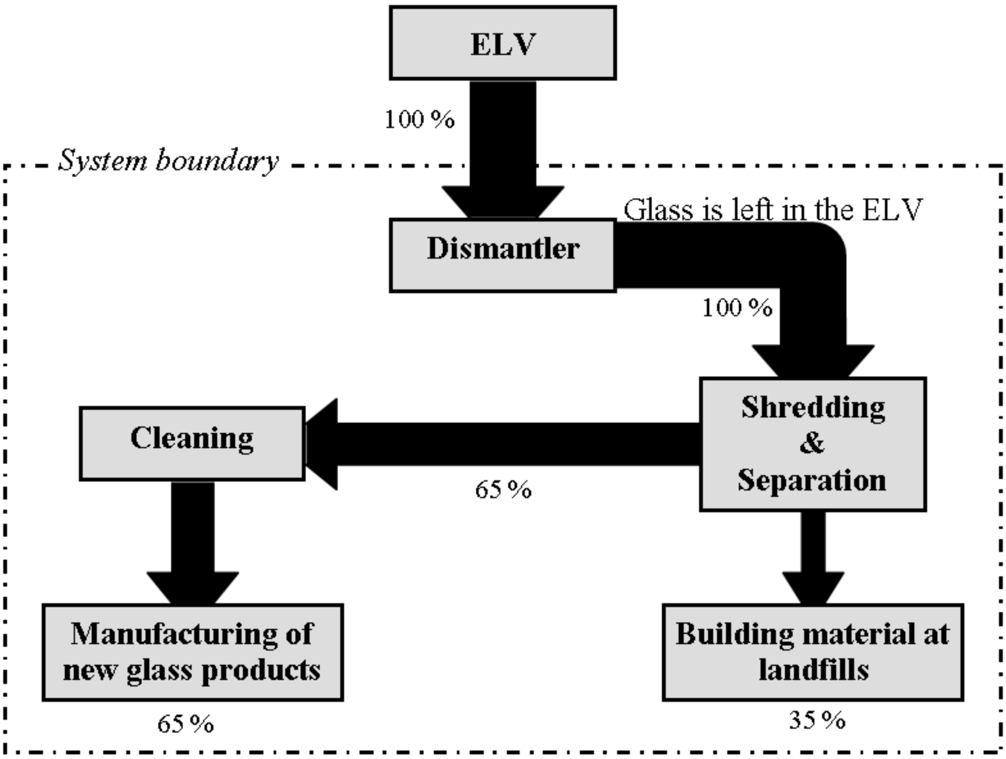

Figure 5: Flow diagram, describing the material flow, of scenario 2.

Table 4: Energy consumptions and CO_2 emissions for one kg of glass entering scenario 2.

Stage	fossil energy [MJ]	electric energy [MJ]	total energy [MJ]	CO_2 emissions [g]
(1) Total transports	0.541		0.541	39.12
(2) Dismantler				
(3) Shredding & Separation		0.457	0.457	52.71
(4) Cleaning	0.073	0.023	0.097	8.47
(5) New glass products	-1.273	-0.546	-1.819	-296.90
(6) Construction material		-0.035	-0.035	-3.98
TOTAL	**-0.659**	**-0.100**	**-0.759**	**-200.58**

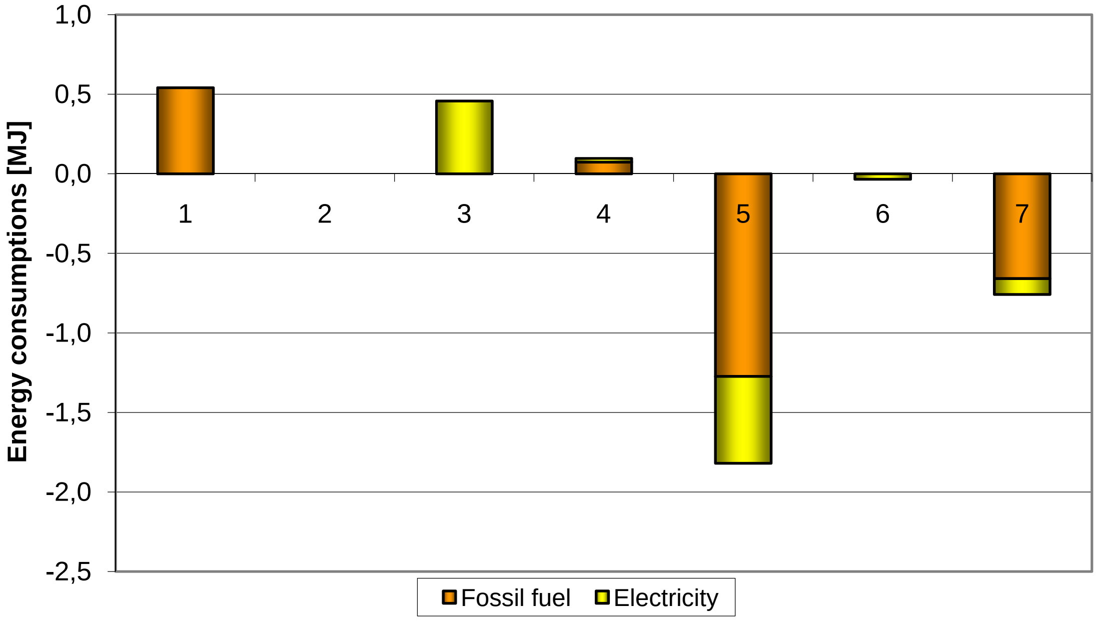

Figure 6: Energy consumptions for scenario 2. (1) Transports, (2) Dismantling, (3) Shredding & Separation, (4) Cleaning, (5) New glass products, (6) Construction material, (7) Total.

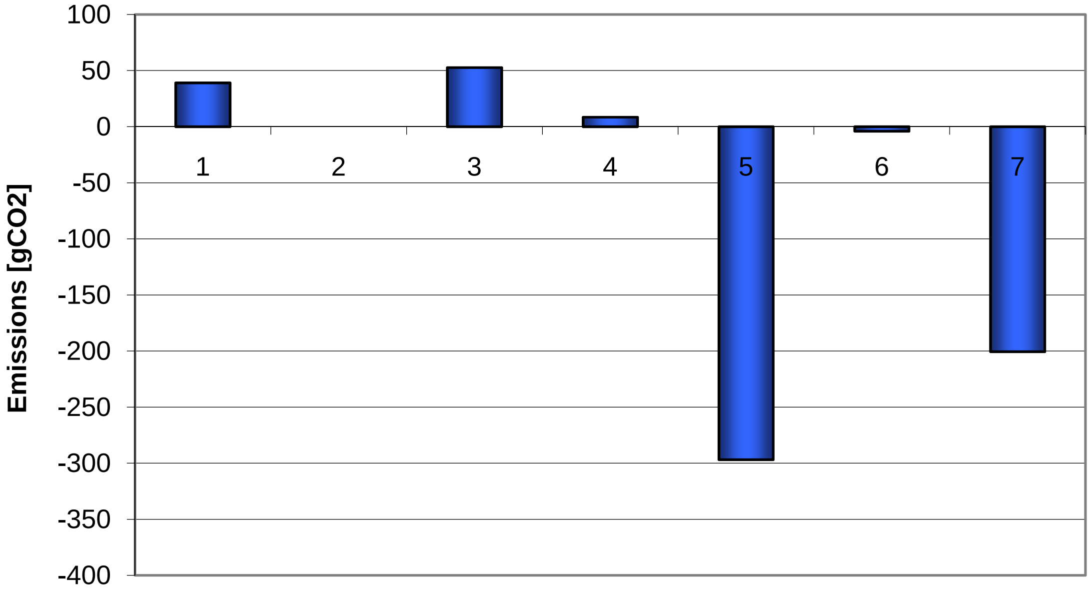

Figure 7: CO_2 emissions from scenario 2. (1) Transports, (2) Dismantling, (3) Shredding & Separation, (4) Cleaning, (5) New glass products, (6) Construction material, (7) Total.

With a separation of 65 % of the glass from a shredded ELV we get a total reduction of 0.8 MJ and 200 gCO_2 per kg of glass. In comparison with scenario 1, we have here a smaller amount of glass recycled as new glass products and thereby also a smaller impact from that stage. The impacts from cleaning and construction material at landfills also changes due to the different recycling ratio. The consumption of fossil fuel from transports is smaller, mainly because a smaller amount is transported on the long route Sweden-Germany-Denmark, but also because some of the glass is transported on the same truck as the ELV to the shredder. A large amount of electricity will be needed for shredding and separation, mainly for pressurized air in the extra sorting equipment. No dismantling is needed and thereby no impact from that stage.

4.3 Scenario 3

The final scenario illustrates what would happen if no glass is dismantled or separated. All glass goes through the shredding and separation process and ends up as construction material at landfills. The flow diagram is illustrated in Figure 8. The energy consumptions and CO_2 emissions are divided into different stages and illustrated in Table 5, Figure 9 and Figure 10.

This is what happens in Sweden today if all of the glass in an ELV is broken, before or after it arrives at the dismantler. The economy around dismantled glass is not in favour for an honest dismantler. Not only will it cost extra manpower to do the dismantling, but it will also cost money to get rid of the glass since it has a negative value [6, 13, 14]. If the glass is left in the ELV it can instead be sold as scrap and become an income for the dismantler.

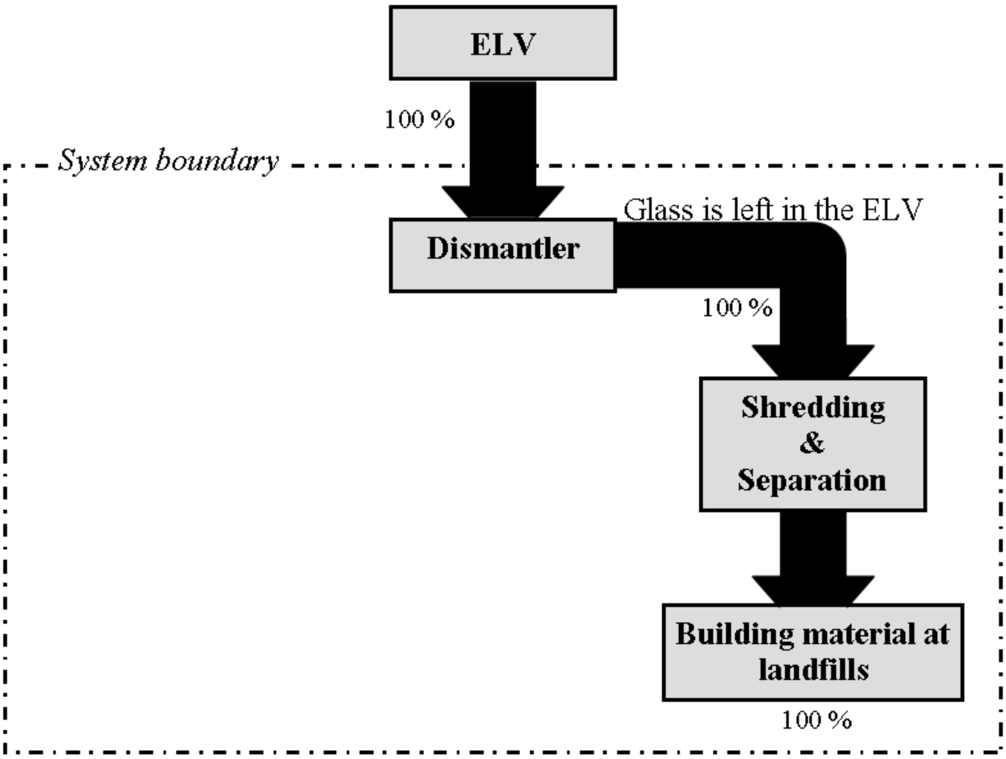

Figure 8: Flow diagram, describing the material flow, of scenario 3.

Table 5: Energy consumptions and CO_2 emissions for one kg of glass entering scenario 3.

Stage	fossil energy [MJ]	electric energy [MJ]	total energy [MJ]	CO_2 emissions [g]
(1) Total transports	0.059		0.059	4.23
(2) Dismantler				
(3) Shredding & Separation		0.007	0.007	0.83
(4) Cleaning				
(5) New glass products				
(6) Construction material		-0.099	-0.099	-11.37
TOTAL	**0.059**	**-0.091**	**-0.033**	**-6.31**

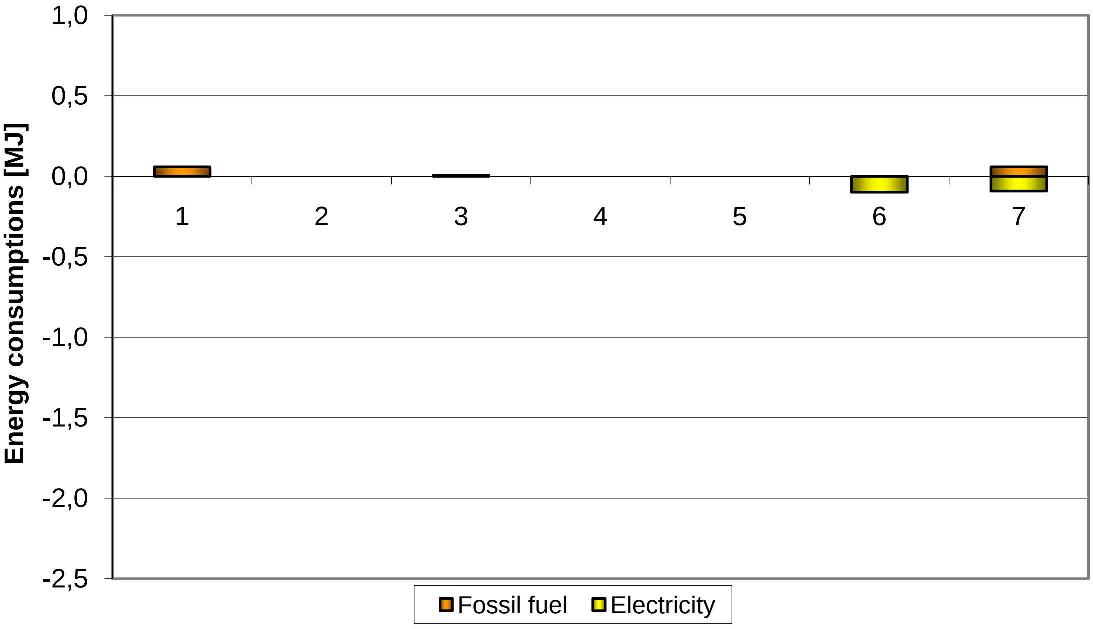

Figure 9: Energy consumptions for scenario 3. (1) Transports, (2) Dismantling, (3) Shredding & Separation, (4) Cleaning, (5) New glass products, (6) Construction material, (7) Total.

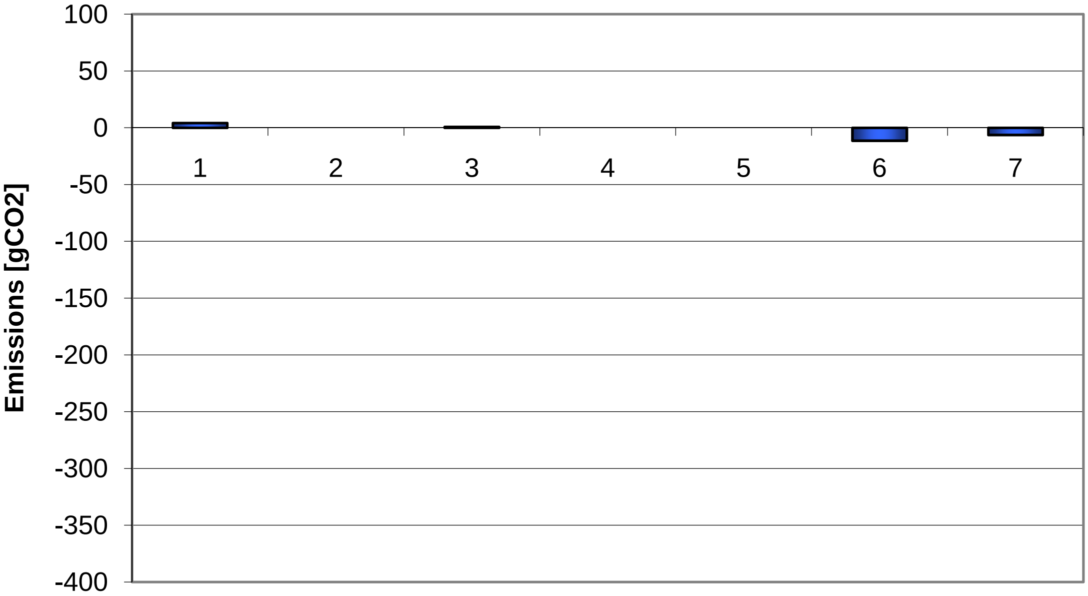

Figure 10: CO_2 emissions from scenario 3. (1) Transports, (2) Dismantling, (3) Shredding & Separation, (4) Cleaning, (5) New glass products, (6) Construction material, (7) Total.

The transports are here reduced to almost zero. The shredding and separation needs more energy in this scenario than in scenario 1, because more glass is shredded. It will, on the other hand, not need any extra sorting equipment and the energy consumption is close to zero. The dismantling, cleaning and manufacturing of new glass products are not happening and thereby no impact from them. There is a small decrease in energy consumption and CO_2 emissions when the glass is used as construction material at landfills. This is due to the reduced need of extracting and transporting sand. Without any dismantling or separation we get a total reduction of 0.03 MJ and 6 gCO_2 per kg of glass.

5 Sensitivity analysis

Some significant assumptions are what type of electricity that will be used, the recycling rates, the transports and the energy consumption from pressurized air in the separation. An even more significant assumption is whether the choice of scenario will have an impact on the recycling of other materials or not. There is a big difference in CO_2 emissions from average electricity and marginal electricity. There is also a big difference in e.g. German and Swedish electricity. The assumption of what type of electricity that will be used will affect all scenarios in a similar way, but make a difference in what type of energy should be preferred; oil and diesel or electricity. The assumption of recycling rates will have a big effect on the result, since the manufacturing of new glass products is the major energy consumer/saver in this study. What types of transports we choose and how far the material is transported will also affect the result. For a fair comparison it is necessary to use similar transports in all scenarios, unless it is impossible to e.g. clean the glass at similar places.

5.1 *Electricity*

We have in this study assumed that all electricity is based on a European (EU-25) average, since the different stages are located in different parts of Europe. For a sensitivity analysis, we have here chosen to compare electricity from EU-25 average (415 gCO_2/kWh) with Swedish average (10 gCO_2/kWh) and coal condense power (ca. 850 gCO_2/kWh) [34]. Coal condense power is what many consider to be the source of European marginal electricity. This is not entirely true, but it is a good example for the sensitivity analysis. Scenarios 1 and 2 are illustrated in Figure 11 with different choice of electricity.

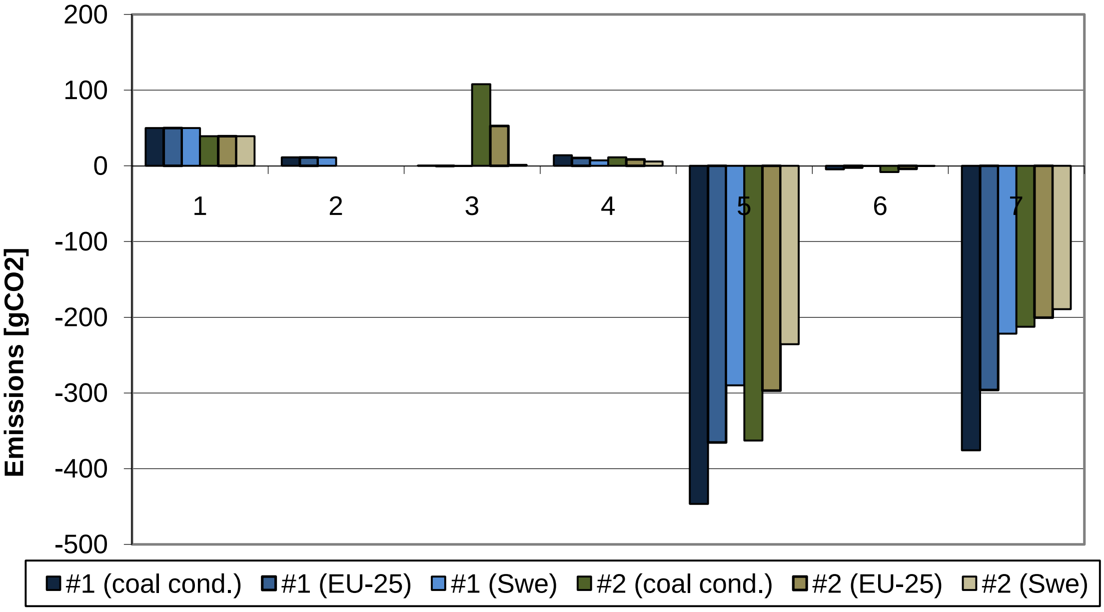

Figure 11: CO_2 emissions from scenarios 1 and 2 with electricity from coal condense power, EU-25 average and Swedish average, respectively. (1) Transports, (2) Dismantling, (3) Shredding & Separation, (4) Cleaning, (5) New glass products, (6) Construction material, (7) Total.

Evidently there will be a big change (105 % increase or 98 % decrease) in emissions from the shredding and separation stage, since we have assumed 100 % electric energy in that stage. The emissions/savings related to manufacturing of new glass products will not change that much. This is due to the assumption that the manufacturing of new glass products saves fossil fuels as well as electricity and due to reductions of CO_2 emissions that otherwise would occur as losses from the melt. Total changes in CO_2 emissions are ± 25 % in scenario 1 and ± 6 % in scenario 2.

5.2 Recycling rate

We have noticed that the recycling (manufacturing of new glass products) has a great impact on the final result. In scenario 1 the recycling rate is equal to how much glass that is dismantled, assumed to be 80 %. In scenario 2 the recycling rate is equal to how much glass that is sorted out after the shredding, assumed to be 65 %. Figure 12 illustrates what the energy consumptions would be if the recycling rates were changed in scenarios 1 and 2. Figure 13 illustrates the CO_2 emissions connected to those energy consumptions. Scenario 3 is here equal to scenario 1 at 0 % recycling rate.

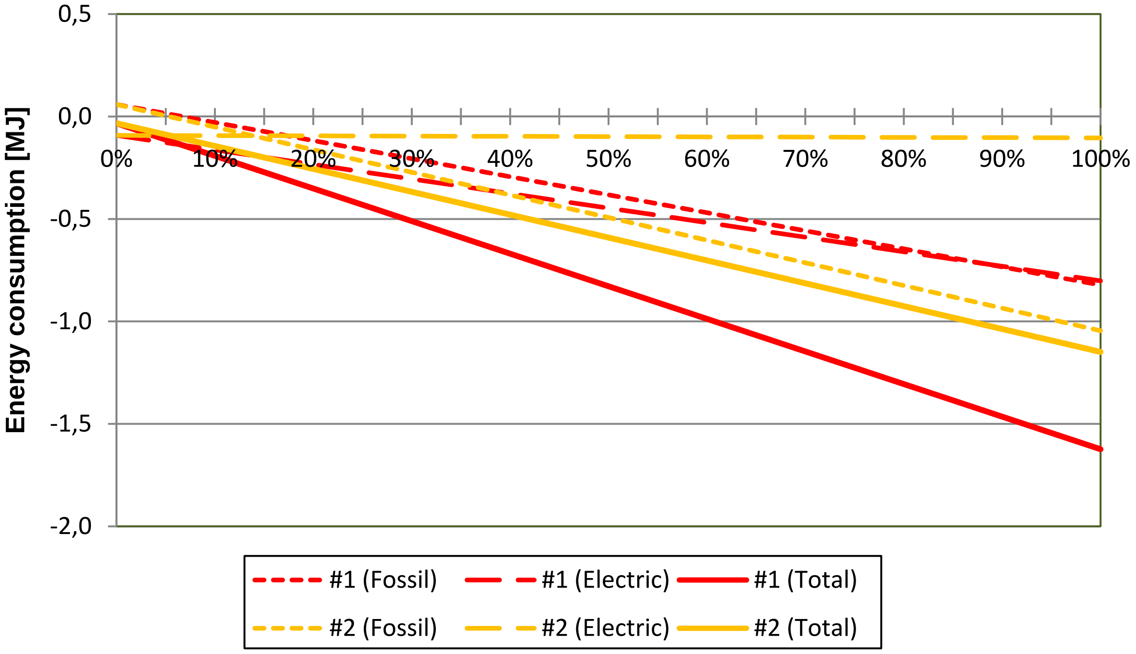

Figure 12: Energy consumption from scenarios 1 and 2 at different recycling rates.

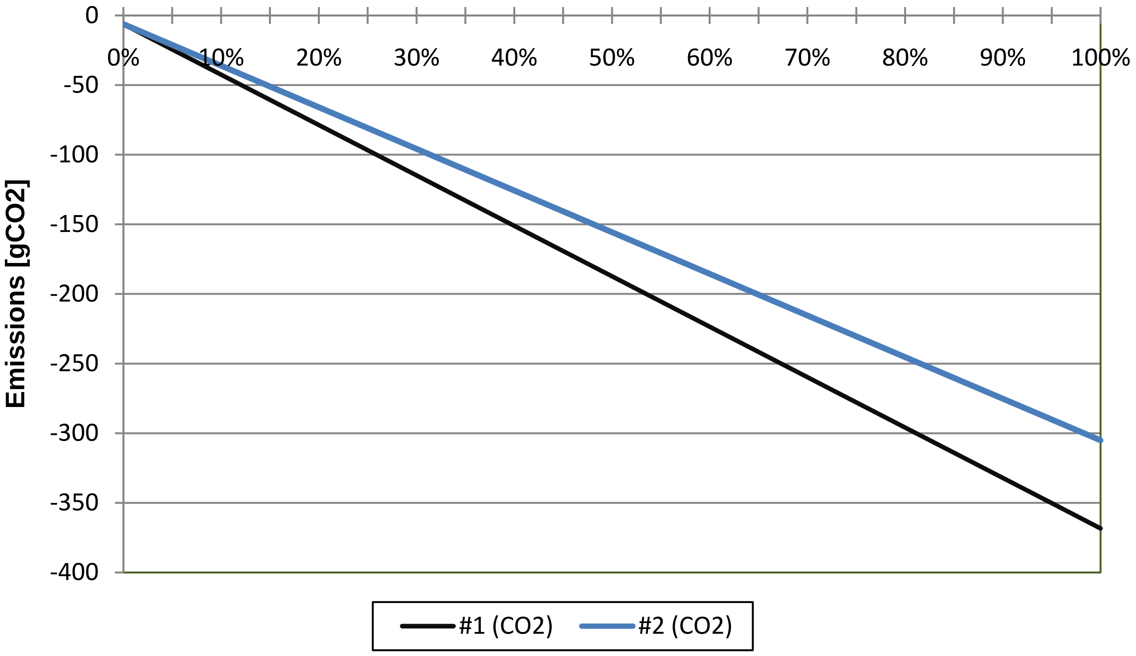

Figure 13: CO_2 emissions from scenarios 1 and 2 at different recycling rates.

Not surprisingly, it is clearly shown in Figure 12 and Figure 13 that a higher recycling rate results in more reductions in energy consumptions and CO_2 emissions. It also shows that there is a smaller difference between scenarios 1 and 2 if they are compared at the same recycling rate. At 65 % recycling rate, the difference between total energy savings from scenarios 1 and 2 is ca. 0.3 MJ/kg. The difference between total CO_2 emissions from scenarios 1 and 2 is ca. 40 gCO_2/kg.

5.3 *End products*

We believe that a big part of the glass from ELVs in southern Sweden ends up as glass wool. Glass from ELVs in middle Sweden ends up as wine bottles. A big part of the glass from ELVs in northern Sweden probably ends up as foam glass [16, 19]. Glass that goes through the shredder, without getting sorted out for recycling as glass products, is used as construction material at landfills. It could also end up as waste or some other kind of filling material, e.g. in the fired bricks industry. How much difference will the choice of end product make?

5.3.1 Glass products

We have assumed that there is plenty of recycled glass on the market, but it is not saturated. We have also assumed that the glass wool producers are willing to pay more for the recycled glass than the producers of container glass. This means that a small change in the supply of ELV glass will, at the glass wool producer, be compensated by an opposite change in the use of some other recycled glass. In the end, it will be the producer of container glass that will have to change ratio between recycled glass and virgin material. This case (a) is illustrated in Figure 14 as 1a and 2a for scenarios 1 and 2 respectively.

Another assumption could be that there is still plenty of glass on a non-saturated market, but the producers of container glass are willing to pay the higher price. This will in our study have the same effect as if the market has a lack of recycled glass. When the ELV glass ends up in a glass wool production, it will also be the glass wool production that changes. The ratio between recycled glass and virgin material will change and thereby also the need for energy and virgin material. In this case we do not know exactly what kind of virgin material that will be substituted in the glass wool production, but it seems similar to the virgin material used in production of container glass. We have therefore assumed the same use of energy for the extraction and transportation of virgin material for glass wool production as for production of container glass. This case (b) is illustrated in Figure 14 as 1b and 2b for scenarios 1 and 2 respectively.

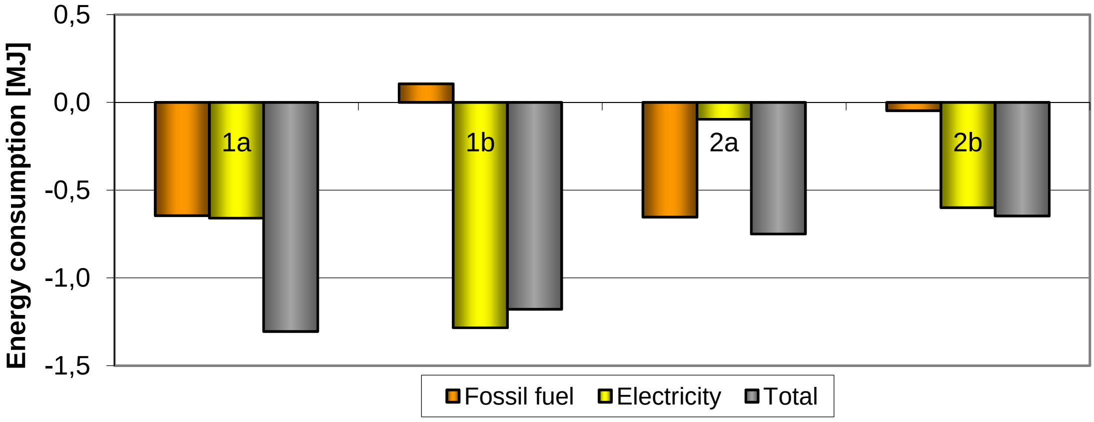

Figure 14: Energy consumptions from scenario 1 and 2. Case a: ELV glass substitutes raw material in the production of container glass. Case b: ELV glass substitutes raw material in the production of glass wool.

There is a small difference in total energy consumption between cases a and b. The big difference is what kind of energy. In case a, the producer of container glass used a big part oil. Hence, there are savings in fossil fuel. In case b, the producer of glass wool only used electricity for the melting furnace. Hence, there are more savings in electricity.

5.3.2 Construction material

The residues from shredding vehicles (ASR – auto shredder residue) consist of glass, organic material and many other components. The glass is today used as a construction material at landfills and the organics are usually sent to landfills as waste. In order to reach the goals of 2015, some of these residues need to be used for material recycling or energy recovery. The glass and organic material can together be used in the fired bricks industry [35]. The glass is used as filler, instead of quartz sand, and the organics is used as a burnable material to form pores in the bricks. The glass can under certain conditions help make bricks with higher quality at lower energy costs. It is uncertain what the total energy savings would be from such a process, since many factors play in. We need to compare the strength and insulating properties between bricks with or without glass. We need to investigate what amount of organic residues from the shredding that will be used in this process instead of becoming waste on a landfill. We also need to investigate what other components (e.g. different metals) that needs to be sorted out from the ASR before it is used for bricks. We cannot compare it in this study, but it is worth mentioning.

It is uncertain how much glass that goes to waste today, instead of construction material. Figure 15 illustrates the two most extreme cases. The first case (‘construction material’) is our base case of scenario 3, assuming that all of the glass is used as construction material. In the second case (‘waste’) we assume that all of the glass in scenario 3 goes to waste. The energy consumptions for the end products are illustrated along with the total energy consumptions for the full scenario.

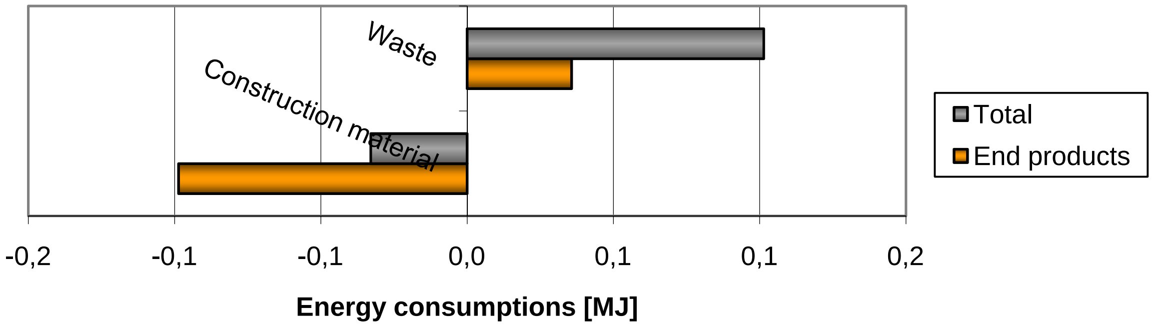

Figure 15: Energy consumptions from scenario 3 with different end products for the glass.

Not surprisingly, the total energy consumption went from negative to positive when we removed the only energy reduction from this scenario and replaced it with an energy consumer. Still, the numbers are quite small compared to scenarios 1 and 2.

5.4 Transports

As stated in section 3.9 the transport routes are different, depending on where the ELV is dismantled. In the base case of scenarios 1 and 2, the glass is transported by truck first to Germany and then to Denmark. The glass can also be transported by boat to Italy. Figure 16 illustrates an example of how scenario 1 would look like with these two transport routes. The energy consumptions for transports are illustrated along with the total energy consumptions for the full scenario.

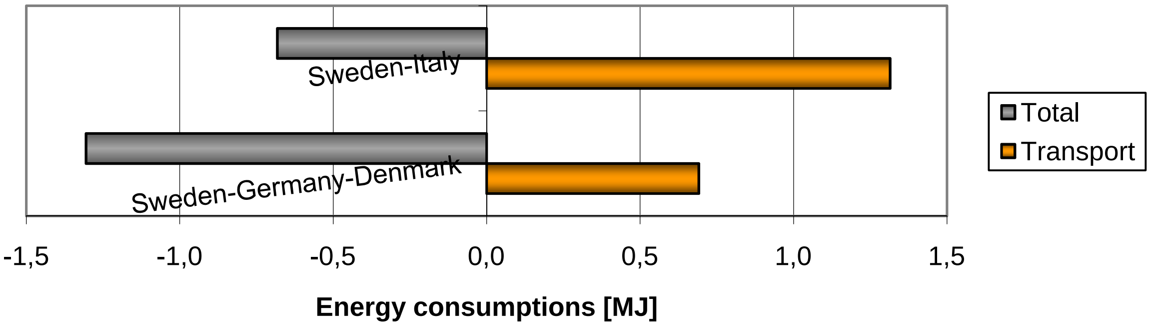

Figure 16: Energy consumptions from scenario 1 with different transport routes of the recycled glass.

When transporting from point A to point B, a boat transport is more energy efficient than a truck transport on the same distance. The glass from Sweden to Italy is transported by boat, but it is a long distance. That distance will suddenly reduce the total energy savings from scenario 1 with almost 50 % (0.6 MJ/kg). Notice that these transport routes are not based on the same starting location in Sweden. The route Sweden-Germany-Denmark starts at a location ca. 150 km from Malmö and Sweden-Italy starts at a location ca. 200 km from Otterbäcken.

5.5 *Shredding and separation*

From the results in section 4 we can see that the shredding and separation stage makes a big difference between the three scenarios. In section 3.4.3 we assumed that the hammer mill will not need any extra energy for the glass that it tears apart, only the iron. We could on the other hand consider glass to be equal to the average scrap going through the shredder, with an energy consumption of 15 kWh per ton input. The difference in total energy consumption would then be 0.01 MJ per kg glass in scenario 1 and 0.05 MJ per kg glass in scenarios 2 and 3. Remember that only 20 % of the glass from scenario 1 goes to the shredder.

The energy consumption from the optical sorting with pressurized air is quite uncertain. It could very well range between 50 % and 150 % of what we assumed. That gives us an uncertainty of ± 0.2 MJ per kg glass, or ± 30 % of the total energy savings from scenario 2.

5.6 *Other recyclables from an ELV*

When we compare glass with other materials we can see that the energy savings from recycling glass is small in comparison. Figure 17 illustrates the reductions in manufacturing energy from recycling various materials. The data (incl. glass) is from a comparison of five different studies of municipal solid waste [36]. Figure 17 illustrates how small the energy savings are when glass is recycled. Recycling of 1 kg glass will result in the same energy savings as recycling of 180 g newspaper, 150 g steel or 12 g aluminium.

The goal for 2015, set up in the ELV Directive, is that the reuse and recovery shall be at least 95 % by an average weight per vehicle. The reuse and recycling shall be at least 85 %. That means that less than 5 % of a vehicle shall end up at a landfill and less than 15 % shall end up at a landfill or be used for energy recovery. Since a car consist of almost 3 % glass, it will be important to recycle as much glass as possible to reach this goal.

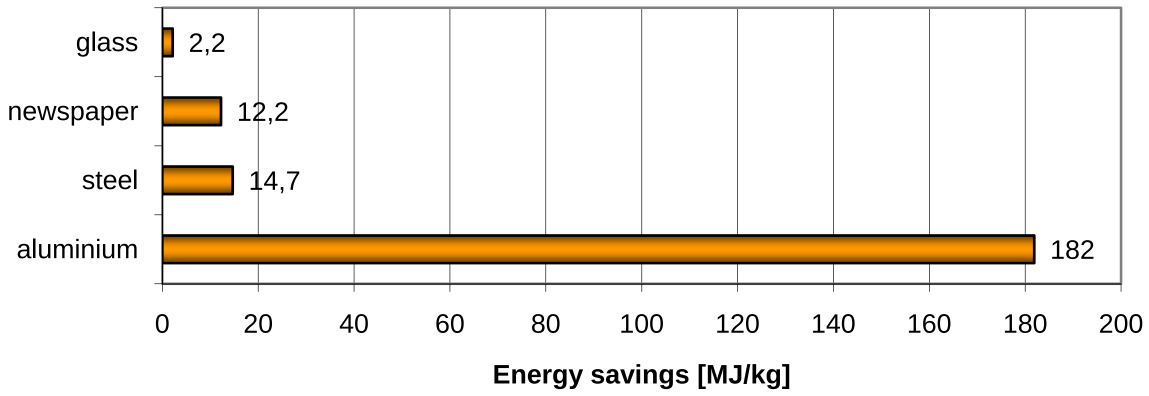

Figure 17: Reductions in manufacturing energy from recycling various materials. [36]

For a sensitivity analysis we will assume there will be exactly 95 % reuse and recovery and exactly 85 % reuse and recycling from an average ELV. With the assumptions that an ELV contains 31 kg glass and that there is 80 % glass recycling in scenario 1 and 65 % glass recycling in scenario 2, there will be 4.65 kg more recycled glass per ELV in scenario 1. This means that 4.65 kg of something else will be recycled in scenario 2, instead of the glass. The extra 4.65 kg can be anything, e.g. plastics, rubber, fabrics or any type of metal.

As an example we assume that all the extra recycling will be from steel. One kg steel will result in ca. 12.5 MJ more energy savings than one kg glass and 4.65 kg steel will result in 58.1 MJ more energy savings than 4.65 kg glass. Distributed over all 31 kg glass from the ELV, this will result in an extra energy saving of 1.9 MJ per kg glass in scenario 2. When we compare that with a total energy saving of 1.3 MJ per kg glass from scenario 1 and almost 0.8 MJ per kg glass from the base case of scenario 2, we see that a decreased glass recycling can result in an increased energy saving. This is illustrated in Table 6.

Table 6: Energy savings from scenario 1, scenario 2 and scenario 2 where the decrease of recycled glass is replaced by an increase of recycled steel.

Description	Total energy savings
Scenario 1	1.3 MJ/kg
Scenario 2	0.8 MJ/kg
Scenario 2 with additional 4.65 kg recycled steel	2.6 MJ/kg

6 Discussion and conclusion

An estimation of 80 % dismantling of the glass in scenario 1 results in ca. 1.3 MJ total energy savings per kg of glass that goes through the dismantler stage. Scenario 2, with 65 % separation of the glass after shredding, results in ca. 0.8 MJ energy savings per kg glass. Scenario 3, with no recycling into new glass products, results in ca. 0.03 MJ energy savings per kg glass. With these assumptions of 80 %, 65 % and 0 % recycling rates in scenarios 1, 2 and 3, respectively, scenario 1 will be preferred before scenarios 2 and 3 and scenario 2 will be preferred before scenario 3.

Since the energy savings from glass recycling are relatively small, a suggestion is to investigate the economics of scenarios 1, 2 and 3. Make a cost benefit analysis to compare the economics with environmental benefits. The environmental benefits might have a different cost in different scenarios.

As it is mentioned in section 5.2, the recycling rate is an important factor of this study. Our assumption of 80 % recycling in scenario 1 is uncertain, merely based on what was observed at two dismantling locations [13, 14]. A suggestion is to further investigate how much glass Swedish dismantlers actually dismantle. By doing that, the actual recycling rate of scenario 1 can be found.

When it comes to regulations for treatment operations of ELV glass, there are at least two ways to regulate. One option is to regulate what type of technique that should be used. The Swedish legislation gives us a technique by saying that the glass should be dismantled before shredding of the ELV. A good recycling ratio can be reached with this regulation, but there will not be much development. There will be no testing of new techniques, since nobody is allowed to use them.

Another option is to set a goal, e.g. a certain level of recycling, regardless of what technique that is used. This is something we can see in parts of Annex I.4 of the ELV Directive, with "removal of [...] if these materials are not segregated in the shredding process [...]". This type of regulation can result in more development, when the companies try to find techniques that can reach the goal in a simpler and more efficient way. Those energy savings that exists today will probably be even larger in the future, since they will also result in economic savings.

A suggestion is to allow a shredding facility to receive ELVs with glass, as in scenario 2, given that there is documentation of sufficient separation. If the amount of separation in scenario 2 is similar to what would otherwise be dismantled in scenario 1, and the separated glass can be recycled as glass material, then it should be allowed to use any of those techniques.

The treatment operations described in Annex I.4 of the ELV Directive are said to be "treatment operations in order to promote recycling". The final conclusions of this study are that both of the scenarios 1 and 2 include treatment operations that promote recycling and as long as there is a decent glass recycling ratio in both scenarios, there will also be decent reductions in energy consumptions and CO_2 emissions.

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