Assessment of the Demand for Critical Raw Materials for the Implementation of Fuel Cells for Stationary and Mobile Applications

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Abstract

Because of their low emissions and possible contribution to sustainable development, both mobile and stationary fuel cells show promising tendencies to play an important role in the future. However, the polymer exchange membrane fuel cell (PEMFC) used in two major applications (i.e. fuel cell vehicles (mobile application) and household Combined Heat and Power systems (stationary application)) contains significant amounts of platinum, a material considered critical within the European Union due to its geological scarcity and highly concentrated supply base. Using material flow analysis, this paper seeks to examine how the implementation of mobile and stationary fuel cells will affect demand for critical raw materials and to what degree recycling presents a viable option for reducing the pressure on primary production. Based on a number of developed scenarios, it is demonstrated that neither the platinum requirements arising from a more widespread adoption of fuel cell vehicles nor the platinum demand from household heating systems is likely to cause a depletion of platinum deposits in the near future. However, both technologies may increase the pressure on the already constricted platinum market, thus rendering this resource even more critical to European industries.

1 Introduction

Both mobile fuel cells in automotive applications and stationary fuel cells in Combined Heat and Power (CHP) household heating systems have not reached market maturity yet, but show promising tendencies to play an important role in the future if these technologies are supported by adequate political decisions. The main driver for both technologies is clearly their low production of emissions during the use phase.

While fuel cell vehicles represent the mobile application of fuel cells (FC), the stationary fuel cells addressed in this paper represent household heating systems only.

In general, the distributed energy generation from stationary fuel cells (SFC) offers significant benefits. With electrical efficiency values of 33% up to 60% under experimental conditions for power-only systems, as well as a combined efficiency in cogeneration higher than 90% [1], SFC exhibit high energy conversion efficiencies, which represents primary energy savings and a reduction of transmission losses. Using natural gas as fuel, SFC can reduce CO_2 emissions due to their efficient conversion of natural gas. Even combustion of natural gas consisting to > 95 % of methane emits per calorific value (in J) about 30% less CO_2 than gasoline, about 60 % less than bituminous coal and even more than 90% less than lignite. In CHP units, fuel cells present a solution to cut building energy use and emissions in the near term, as the technology can make use of existing fuel distribution infrastructure [2].

Unlike battery electric vehicles, fuel cell vehicles are comparable to internal combustion engine vehicles with regards to driving range and performance and can be considered the lowest-carbon option for medium to long-distance trips. Since this segment represents 75% of today's passenger vehicle CO_2 emissions, substitution of one combustion engine vehicle with a fuel cell vehicle (FCV) achieves a comparably higher CO_2 reduction [3].

In developed regions, particularly in Germany, Japan, South Korea and the United States, the fuel cell industry has gained traction in recent years [4].

However, the catalyst material platinum, which is generally applied in the polymer exchange membrane fuel cell (PEMFC) used for both mobile and stationary fuel cells, has attracted the world market's attention since it was classified as highly critical as part of the European Commission's assessment of critical raw materials [5]. In addition to the significant environmental impacts caused by the extraction of platinum group metals (PGM), including emissions of sulphur dioxide, of CO_2 equivalents in the range of 13,000 tons per ton of PGM [6], excessive water and energy consumption [7], habitat destruction, air and water pollution and generation of dust, particulate matter and solid waste [8], platinum is considered a critical metal in the EU due to its geological scarcity, its use in a variety of technologies and its highly concentrated supply base [5].

Metal recycling is considered an important strategy for lowering the pressure of primary deposits and the environmental impacts of extraction, as well as increasing the economic benefit of the metals in use [9]. The recycling of platinum is already well-established and can therefore act to fill gaps within the primary supply chain of platinum. This internal ability for supplying secondary raw materials from recycling can serve to make the European Union (EU) more independent of other continents' suppliers. However, recycling rates vary significantly between different applications. While valuable precious metals, including platinum, typically have high recovery rates, the recycling rates for certain

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consumer applications are disturbingly low. Passenger cars represent one such application with relatively low platinum recycling rates, as the recycling quotas for exhaust gas catalysts reach a mere 50% to 60% [10]. This makes the automotive industry the largest net consumer of platinum today, even when growth of vehicle sales is ignored [11].

It is therefore in the interests of both fuel cell and car manufacturers to close these loops and focus on the contribution of recycling for meeting their future platinum demand. The same holds true for the newly established technology of fuel cells in household CHP units, for which no collection and recycling is taking place so far since very few fuel cell CHP units have reached the end of their useful lifetime as of 2018. In addition to PEMFC in stationary application also Solid Oxide fuel cells have entered the market in household application, where platinum does not play any role. However, it is not known which technology is preferred by which company and the data is very poor. In order to assess supply issues of the main catalyst material used in both technologies and thus explore the sustainability of these alternative sources of energy, this paper seeks to examine how the implementation of mobile and stationary fuel cells will affect demand for critical raw materials and to what degree recycling presents a viable option for reducing the pressure on primary production.

The paper is structured as follows: Section 2 provides an overview of the state of the art for fuel cells in both stationary and mobile applications. A material flow assessment of the relevant fuel cell materials, with a strong focus on platinum is applied in Section 3, while Section 4 concludes with a discussion of the results.

2 Theoretical Background

2.1 Characteristics of Fuel Cells

From a structural perspective, fuel cell vehicles can be considered a type of hybrid vehicle, in which the fuel cell replaces the internal combustion engine [12]. Using atmospheric oxygen and compressed gaseous hydrogen supplied from the onboard tank, the fuel cell generates electricity, which powers the vehicle’s electric motor. Due to their favorable attributes, such as low operating temperature, fast start-up and fast response to varying loads, FC installed in automotive applications are currently only of the PEMFC type (status 2017).

A more detailed description of the structure and functioning is provided by, e.g. [13]. In summary, in PEMFC a platinum-based catalyst is generally used for both the oxidation reaction taking place at the anode and the reduction reaction occurring at the cathode. Particles of the catalyst (10 to 100 nm in size) are finely dispersed on a porous substrate, which usually consists of high surface area carbon powders, e.g., carbon black. Commercial production today typically employs procedures like those of the printing industry, in which the supported or unsupported catalyst material is mixed with solvents, binder (perfluorosulfonic acid or other ionomers in protonated form) and other additives to form a “catalyst ink” and then applied in wet form [13-16].

Assuming a fuel cell stack of 80 kWe, the platinum loading reported for 2013 still translates into a total platinum requirement of around 20 g per fuel cell vehicle. Moreover, as these are fuel cell stacks produced and tested under laboratory conditions, the platinum load of fuel cell stacks installed in FCV technology currently ‘on the road’ is likely still higher. Due to the proprietary nature of such data, exact and reliable numbers for the platinum content of FCV models manufactured today cannot be obtained; instead, assessment of the current platinum load relies on estimates and proposals published by automobile manufacturers and researchers [13].

For fuel cell-generated energy supply, two fuel cell types are mostly used. The most developed technologies for stationary applications up to 10 kWe are the PEMFC and the Solid Oxide Fuel Cell (SOFC); for fuel cells in mobile applications, mainly automotive, the PEMFCs dominate.

Based on thermodynamics, PEMFCs can reach efficiencies in the conversion of chemical energy (fuel) to mechanical energies at the wheels up to 95%, whereas classical combustion energies are limited to about 40%, due to the unavoidable Carnot process conditions. They have great technological potential as their development is already advanced due to their similarity to the ones used in automotive applications. The PEMFC for domestic energy supply is a low-temperature version with an operating temperature in the range of 80 °C, while the high-temperature mobile version can oscillate between 160 to 180 °C. PEMFC are also attractive to the residential CHP market because of their relatively compact size and the fact that they do not require insulation. PEMFC systems are to run with pure hydrogen. Since hydrogen is currently mostly obtained from natural gas by steam reforming or other fossil fuels by partial oxidation, carbon monoxide (CO) has to be removed first, since CO acts as an effective poison for the platinum catalyst due to strong adsorption. This adsorption is especially problematic at low operation temperatures below about 140°C. Thus, the hydrogen fuel has to be carefully reformed before entering the system [17].

As with PEMFC in automotive applications, a platinum catalyst is generally used for both the oxidation reaction taking place at the anode and the reduction reaction occurring at the cathode. Although the platinum content is considered one of the main cost drivers of PEMFC [13], the amount of platinum required in SFC is even higher than in mobile FC. This is due to the continuous requirement on operations, which necessitates loadings in the range of 0,75 g platinum/kWe for stationary applications in comparison to 0,2 g platinum/kWe for mobile ones [18]. The catalyst metal influences not only the specific power, but also the fuel cell’s lifetime.

In contrast to PEMFCs, SOFCs operate at a temperature level of 650 to 850 ° C. In this temperature range, according to thermodynamics, fuel cells do not work more efficiently than gas-fired combustion engines, however, they can be very easily build as CHP units. Compared to PEMFC, SOFC have the advantage of an easier gas treatment since CO adsorption is no longer possible at this high temperature [19]. SOFC are expected to be more economical in sizes above 1 MW (Brown et al. 2007, p. 2176). While the SOFC does not contain platinum, other critical materials provoke equal concerns regarding security of supply, price stability and sustainability.

Yttria (yttrium oxide) is a critical material commonly used in SOFC membranes. The yttrium oxide is used as a dopant (about 8 wt.-%) in the zirconia (ZrO_2) in order to ensure the necessary conductivity of oxide (O^{2-}) anions. While zirconium can be considered as an element under observation with respect to the availability, yttrium is a rare-earth element (REE), and is categorized as a critical metal due to its low availability (around 9 000 t/a of production), and the concentration of its reserves. The problem of recycling of REE including yttrium is that in applications they are mostly used in low concentrations and in strong interaction with other elements. Recycling of these mixed compounds by the common route of employing redox-active ligands is often difficult since the chemical coordination properties of the different elements might be similar [20]. For recycling via electrochemical separation typically the thermodynamic rules the process. Since this is not useful for REEs, here the kinetics must be used to control the separation [21]. Thus, e.g. low temperatures might be favourable. Other potentially problematic materials include scandium, lanthanum and cobalt.

Although the SOFC technology is not addressed further in this paper, the issues concerning critical materials such as Yttrium should be examined once the market for SOFC demonstrates a higher maturity.

2.2 Market Application of Fuel Cells

Stationary Fuel Cells (SFC) refer to units designed to provide power at a fixed location. They include small and large stationary power supply, backup or uninterruptible power supply, combined heat and power, and combined cooling and power. SFC can be applied in various stationary applications, ranging from systems under 1 kWe for CHP, larger units (several kWe) for district heating or large buildings, up to MWe applications for industrial cogeneration and electricity production without cogeneration. Different conventional systems are already well established for each of these applications, such as gas engine CHP, gas turbines, or combined cycle power plants [22].

They can be broadly divided into two types: power-only and cogeneration systems. The power-only type includes back-up or uninterruptible power systems fuelled by hydrogen [23]. Cogeneration systems use the electric output and the waste heat for heating applications. With around 665 TWh [24], the energy used by the 18.9 million German households [25] accounts for around 26.2% of the total final energy use. The majority of CHP systems for domestic energy supply (micro-CHP) in the market correspond to the following technologies: Otto Motor, Stirling Motor, Steam Expansion, Organic Rankine Cycle (ORC), Micro-Gas turbine, and SFC [26].

Replacing conventional gas boiler systems, natural gas fuelled micro-CHP systems are expected to become one of the first major mass markets for FC. This product can be described as a mass-produced appliance targeted at residences (single and multi-family), and small commercial users [27]. The power produced is preferentially used within the building, with top-up and backup power supplied from the grid. In addition, any excess power produced is also exported to the grid. The size of domestic application systems typically ranges between 500 We and 5 kWe, with small commercial units reaching up to 50 kWe [27, 28]. For industrial-sized applications, SFC systems can reach ranges of 200 to 500 kWe [28].

Deployment of the system is oriented towards maximization of the efficiency [18], i.e. the energy output. Compared with electricity generation in central power plants and heat generation, SFC demonstrate a 30% better utilization of the fuel [27]. Further advantages include short startup times, a high cycle stability and good partial load capacity, making them suitable for intermittent and load-variable operation. Disadvantages, on the other hand, include high purity of the required fuel, for which a technically complex gas purification process is necessary [29].

In contrast to SFC [30], the mobile FCs have already entered the market and are beginning to compete with conventional combustion engines vehicles and other alternative powertrain technologies. The limited availability of hydrogen fuelling stations continues to be one of the greatest obstacles for market penetration of FCV. The expansion of the hydrogen station network is largely taking place in certain lead markets, including California (which has 33 hydrogen fueling stations serving approximately 4,200 FCV), Germany (45 hydrogen stations) and Japan (91 hydrogen stations) [31]. In Europe, two different FCV models are currently available for purchase, although this number is likely to expand as other manufacturers enter the market [32]. Future development of the FCV market is likely to depend both on private investment decisions and on the political endorsement of FCV technology.

3 Methodology of Material Flow Analysis

Recovering metals from complex and low-grade materials can be more energy intensive than supplying them from raw ores. In many cases, however, the recovery of secondary metals is less energy intensive than mining, as the metal concentration in many products is higher than in ores. This is the case, for example, for precious and rare metals in electronic products [33]. In order to examine not only the demand for critical metals arising from the implementation of stationary and mobile fuel cells, but also the viability of meeting a portion of this demand through recycling, it is therefore vital to assess the amount of recoverable metals accumulated in end-of-life products. As method for assessing the amount of materials we chose Material Flow Assessment (MFA), since it is based on the principle of conservation of matter or mass balancing (i.e. input equals output). It is closely linked to the concept ‘metabolism of the anthroposphere’, which can be understood as an analogy to the human or natural metabolism. While a more detailed review of this idea is beyond the scope of this paper, suffice it to note that the concept imitates the continuous cycling of material and energy present in biological processes and has been used to analyse and describe urban and regional material balances, especially for the purpose of environmental protection and waste management. The dynamic MFA for this paper is performed using the software tool STAN (short for SubSTance flow ANalysis), which is a freeware developed by the Institute for Water Quality, Resources and Waste Management at the Vienna University of Technology in cooperation with INKA software.

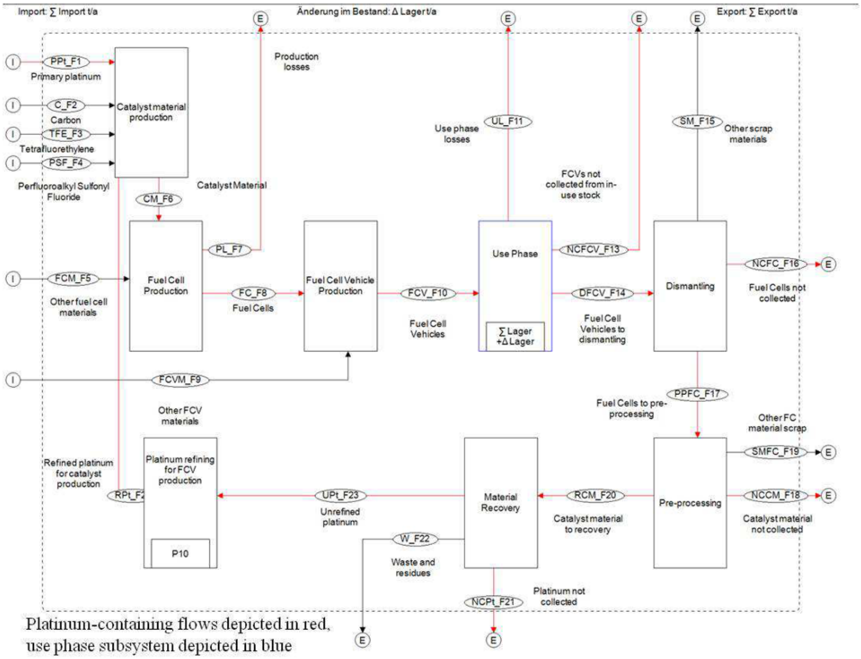
3.1 Material Flow Analysis for Automotive Fuel Cells

The model of platinum flows (Figure 1) arising from a further market penetration of fuel cell vehicles is developed applying a top-down approach: Figures for the future vehicle stock are derived from the two conservative scenarios for market penetration developed by the European Commission [34]. This report was selected from a number of studies because it covers the most far-reaching time horizon (2010 to 2050) and for the equally important reason that the contained data is easily accessible. Based on sociological, technological and economic analyses as well as extensive interaction between science and industry experts from a range of member states, the study produced market penetration scenarios for various hydrogen-based technologies, including four on FCV. In doing so, the study focuses on the following ten European countries, which hence also form the geographical focus of the MFA presented in this paper: Finland, France, Germany, Greece, Italy, the Netherland, Norway, Poland, Spain and the United Kingdom. Of these, Greece was later excluded in this study due to a lack of data on vehicle ownership. Given the current state of the FCV, the assumptions underlying the two more conservative scenarios appeared closer to reality.

In addition to the market penetration scenarios described above, certain assumptions have been made concerning technical aspects. These include the current and future platinum load per kWe installed power, material leakage during the FCV use phase, as well as production and assembly of FC and FCV and the respective efficiencies of these processes.

The calculation originates from the FCV market penetration ratios given by the two scenarios in [34] which are applied to the analysed EU member states’ extrapolated vehicle stock to derive the absolute number of FCV in use per annum over the considered time scale of 35 years. In the next step, the annual energy requirements (kW/a) are calculated from the number of newly registered FCV per annum. Applying to this the platinum load per kW of the respective year as well as any losses occurring in the production stage, one can then determine the gross platinum requirements per annum.

In order to determine the net platinum requirements (Figure 2), the potential supply from recycling is then calculated. Based on two recycling scenarios (i.e. “Baseline”, applying efficiencies currently reported in literature, and “Pro-Recycling”, assuming a highly efficient recycling chain), any platinum losses throughout the use phase and within the recycling chain are subtracted from the potentially available platinum content of end-of-life FCV assuming a vehicle lifetime of 10 years.



Platinum-containing flows depicted in red,
use phase subsystem depicted in blue

Figure 1. STAN Material Flow Analysis model for automotive fuel cells

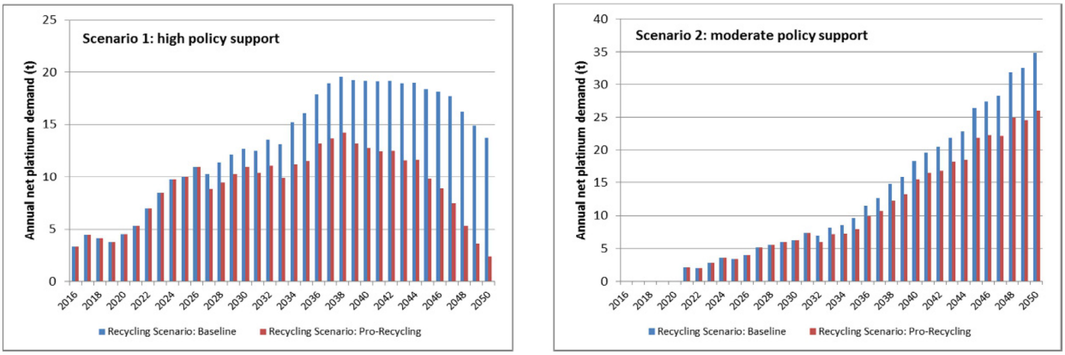


Figure 2. Net platinum demand in Scenario 1 (left) and 2 (right) following two recycling scenarios

From these calculations, the cumulative gross demand for platinum, the cumulative amount of platinum recovered through recycling and the amount of platinum lost through recycling inefficiencies can be determined. These results are summarized in Table 1. The various material efficiency ratios of production use phase and recycling are used as transfer coefficients and transferred into the MFA software, together with the values obtained from the aforementioned calculations. A detailed description of the market penetration scenarios, the two recycling scenarios and the specific calculations can be reproduced by conferring to [13].

Table 1. Cumulative demand and amount of platinum recovered per scenario (adapted from [13])

	Scenario 1 (high policy support)	Scenario 2 (moderate policy support)
Cumulative gross platinum demand	537.06 t	459.24 t
Cumulative amount of platinum recovered (Baseline scenario)	84.8 t (208.71 t lost)	44.85 t (110.38 t lost)
Cumulative amount of platinum recovered (Pro-Recycling scenario)	230.02 t (63.49 t lost)	119.17 t (36.06 t lost)

Both the annual platinum requirements and the cumulative platinum requirements shown above indicate that the diffusion of FCV according to either scenario will have a significant impact on global platinum demand. At this point in time, it is impossible to establish in how far any platinum demand from the fuel cell industry will be additional to or replace the demand from other areas of application, such as that of automotive exhaust gas catalysts. The results of Table 1 also demonstrate that the diffusion of FCV will not cause the depletion of platinum resources, as the calculated 537.06 t and 459.24 t cumulative platinum requirements are far below the currently estimated reserves of 66,000 t of platinum group metal reserves, even though any contribution from the recycling of FCV is not yet included in this extrapolation. At the same time, it must be emphasised that these figures consider only nine European lead markets. A similar level of market penetration in other parts of the world could therefore increase the required quantities of platinum dramatically.

In contrast, a comparison of the maximum annual net demand established by the two scenarios with the current global supply shows that the future platinum requirements for European FCV production only could place a significant strain on the global platinum market. With peaks of 19.5 t and 26.06 t, respectively, the European FCV industry alone would require a maximum of 12% and 16% of the 161.74 t produced in 2014. This could not only lead to significant price increases, but also raises the possibility of supply shortages as well as the dependency of a number of industries on a critical resource and emphasises the importance of recycling.

With regards to the role of recycling in meeting the platinum requirements of a growing FCV fleet, Figure 2 and Table 1 show a significant recycling potential, the exploitation of which could greatly reduce this industry's dependence on the volatile platinum market. Nonetheless, in both Scenario (1) and (2) the discrepancy between the two recycling scenarios becomes apparent. Considering the entire time span from 2016 to 2050, Table 1 lists the cumulative platinum demand for FCV as well as the shares recovered under the four scenario combinations. While the platinum losses are substantial even in the Pro-Recycling scenario, the losses documented as part of the Baseline scenario are excessively high.

3.2 Material Flow Analysis for Stationary Fuel Cells

In addition to automotive fuel cells, a model for Material Flow Analysis on PEMFC stationary fuel cells is constructed to analyse the demand for platinum, considering the different recycling scenarios for end-of-life (EoL) products (Figure 4). The model is divided into different stages: Raw Material Acquisition, Production, Use, and EoL. For each process, transfer coefficients (TF) are defined as fractions that are either lost from the system or are reincorporated to the EoL recycling process. Values for the transfer coefficients (as depicted in Table 3) are taken from literature sources when existing, or assumed by the authors after comparing them to similar technologies, under consideration of the uncertainties that come with these values. 15% of the catalyst material is lost in the electrode coating process, with the ratio of process losses improving continuously. Process losses in the region of 5% to 20% can be expected for automated, industrial-scale coating of membrane rolls, with a catalyst ink scrap rate of 10% [13]. Fraunhofer IPA, as quoted by [35], suggests the typical overspray losses for different coating methods depends on the specific method used as well as the workpiece structure, and can be as high as 90%. Additional losses can occur during the process of fabrication of the fuel cell stack, as a fraction of the manufactured PEMFC CHP units may not comply with quality control procedures. Assuming a high value of confidence for the manufacturing process, the fraction of discarded products is usually lower than 2% [36, 37] with target values of 0,1%.

The technical life time of the stack for future technological configurations is required to be at least 6 years to be commercially applicable [38], with lifetimes assuming 5 000 h/a of operation for intermittent residential operation. Calendar lifetimes would be lower for commercial and industrial installations with longer running hours [39]. The amount of PGM lost in the exhaust of a fuel cell system over its operation is insignificant [40]. [41] indicates use phase material losses of 0,35%/a, and values of 0,68%/a are used by [13] for mobile FC. Due to the continuous operation in stationary applications, this value is also applied.

Recovery rates for PEMFC for automotive applications are estimated to be greater than 95%. The high technical recyclability of PGM means that over 95% recovery can be achieved once platinum-containing products reach a state-of-the-art refining facility [10]. An overall global recycling quota for platinum of 70% (currently about 45%) should be the minimum target for 2020 [42], and 80% for 2030 [43, 44]. For SFC no recycling has taken place so far, but a high recovery rate as in mobile application is expected. Because of the need for having a heating expert in order to change the heating system, a loss of end-of-life systems by both legal and illegal export and recycling activities is unlikely.

Since stationary fuel cells have entered the market only recently and data availability, especially with regards to the use phase, is very poor, the MFA was performed considering only household installations within Germany until 2050. Therefore, this analysis of the housing market in Germany is based on estimations for the number of residential units to be constructed, replaced or renovated, as these units are a potential market for new SFC CHP units. Replacement of conventional operating systems for SFC CHP units is not deemed as economically feasible, hence only new units are considered. The different scenarios assume that SFC run on natural gas or syngas, so existing infrastructure is used [28].

Almost a third of the energy demand in Germany corresponds to housing and buildings. A portion of this is used for warm water and space heating. More than 17 million residential heating devices in Germany produce heat by burning gas and oil [19].. More than three quarters of the residential buildings are heated by central heating. About 15.1 million of these devices are installed in One- or Two-family houses, while 2.3 million gas and oil-burning devices are installed in multi-family houses [26]. One-family houses (OFH), small multi-family houses (SMH), and large multi-family houses (LMH) with 7 to 12 units , as well as large residential buildings (RBH) with more than 13 units, are the principal potential markets for SFC [29]. The number of buildings and its annual evolution corresponds to the sales market and the potential number of CHP plants.

Natural gas is used in 47.8% of the OFH and SMH, and in 47.7% of the larger residential buildings [25]. Micro CHP units with 1 to 2 kW_e and 3 to 10 kW_{th} power based on the Otto and Stirling engine and SFC technologies provide this energy [26]. A residence with 4 people demands an average of 5 MWh_e/a. This represents 570 W of average power. Most of the household applications will be smaller than 1 kW [19].

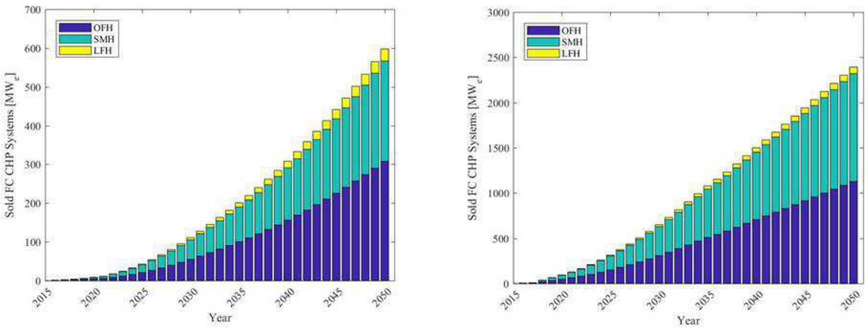
The market for new CHP units is related to the number of new buildings, units required as replacement for demolished units, and renovated units in which the insulation and heating systems are upgraded. Yearly rates are used to estimate these units. [29] presents two different scenarios for this development. In the Reference Scenario, the expansion rates are fixed at 0.5%/a. In the Ecological Scenario, the expansion rates are continuously growing and are set so that by 2050, all buildings existing before 1998 have been either replaced or renovated. To estimate the future market potential of SFC, this technology is assumed to achieve a market share of 90% within the CHP household applications market by 2050 under all scenarios [46]. The application of these values results in the number of buildings requiring a new heating system. Considering the fraction of residential buildings that use natural gas (44.7%) the potential market for FC CHP systems is calculated using forecasted rates for entrance of FC technology. [29] proposes increasing penetration rates of the technology into the market. Two scenarios are used for modelling: Scenario A (Ecological Scenario), of fast introduction of technology, and Scenario B (Reference Scenario), of slow introduction of technology. Both scenarios still consider a technology testing period. The number of FC CHP units for each residence type is calculated based on the above given distributions.

Performing simulations, [29] already determined the optimal size of a SFC CHP system for economic feasibility. Two business models for use of the SFC CHP units are considered: Private User and Contracting model. Each model results in different optimal sizes ranging from units smaller than 1 kWe to larger than 10 kWe (Table 2). RBH are not considered due to their small number.

Table 2. Optimal installation size of FC CHP units. Data from [29]

Building Type	**Private User**			**Contracting Model**		
	Financially feasible size		Operation Hours	Financially feasible size		Operation Hours
	[kW$_e$]	[kW$_{th}$]	[h]	[kW$_e$]	[kW$_{th}$]	[h]
OFH	0.5	0.7	5 700	1.8	3.6	4 400
SFH	2.0	2.9	4 800	6.0	8.6	5 500
LFH	5.0	7.1	6 500	11.0	15.7	5 200

The values of operation hours and the models for failure rates are used to calculate the number of SFC CHP units that need to be placed into the market, as units for new systems or as replacement for existing systems. The Private User model is applied to the reference scenario, while the Contracting Model is applied to the Ecological Scenario. The results indicate a growing market for SFC, with close to 800 thousand units required by 2050 under the highest demand scenario. Although the number of houses with CHP systems varies, an extended operating lifetime for the Ecological Scenario reduces the demand. The total amount of SFC can be quantified in kWe of peak power placed in the market, which is obtained multiplying the number of units and the individual optimal power (Figure 3).



a) Reference Scenario b) Ecological Scenario

Figure 3. FC CHP units placed in the market, in MWe [47]

The value of platinum content in units coming in and out of the service phase is used in a MFA model (Figure 4) to calculate the required input of raw material. The model considers losses in different production stages, and different recovery rates for EoL stages. The values from the transfer coefficients (TC) for each step in the MFA Model are taken from literature sources when existing or assumed by comparing them to similar technologies. A model is built in Simulink 9.0, which allows further analysis of dynamic scenarios and uncertainties.

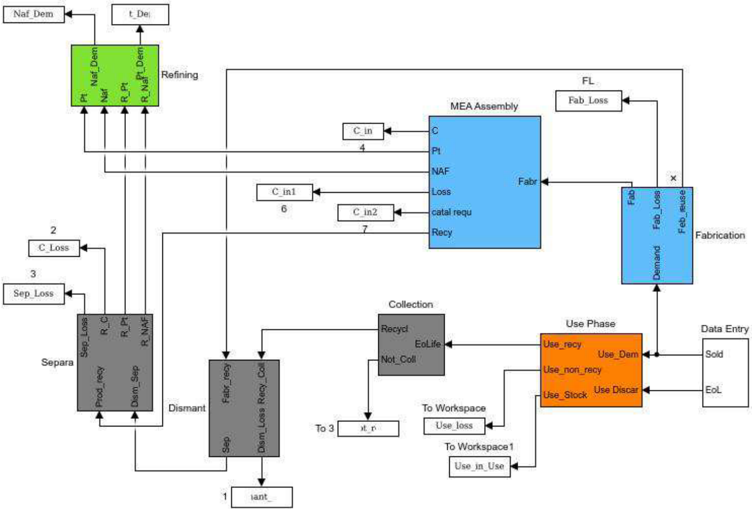


Figure 4. Simulink model layout for MFA

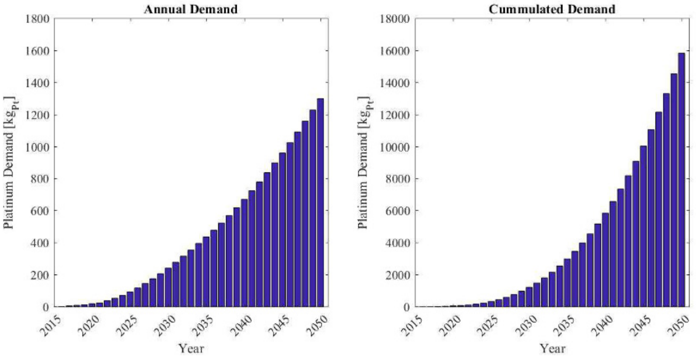
The Reference Scenario assumes values for the transfer coefficient on the lower spectrum of the values found in the literature review, and assumes these values remain constant, i.e. without improvement. The Ecological Scenario assumes higher values and a continuous improvement in the recycling and collection transfer coefficient, and a reduction in production and fabrication losses.

Table 3. Transfer coefficients used for MFA

Value	**Reference Scenario**	**Ecological scenario**	
		Start (2017)	Target (2050)
MEA production loss	40%	15%	5%
FC production loss	50%	2%	0.1%
Recollection rate	15%	60%	95%
Dismantling loss	3.4%	3.4%	1%
Separation loss	10%	5%	1%

A maximum of 1.3 tons of platinum for the Reference Scenario and 0.18 tons of platinum in the Ecological Scenario are estimated to be required annually as raw material input for the supply of PEMFC units for until 2050 for heating applications in German households (Figure 5). Due to improvements in recycling and stabilization of the demand, the ecological scenario presents a further reduction of annual raw platinum demand. In contrast, the input of platinum in the manufacturing stage reaches 3 tons of platinum for the Reference Scenario and 2 tons for the Ecological Scenario. The difference between the demand for raw material and material input for manufacturing are due to improvements in recycling.

a) Reference Scenario



b) Ecological Scenario

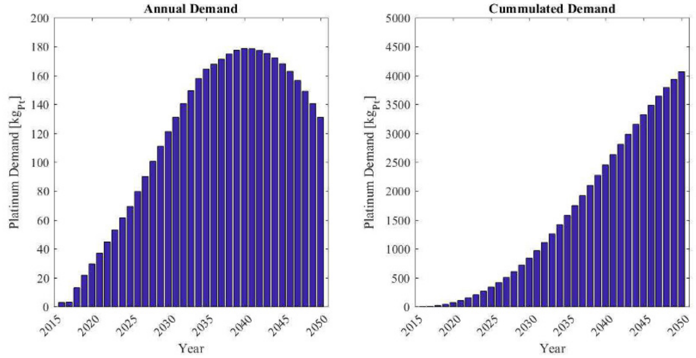


Figure 5. Values of yearly and accumulated platinum demand [47]

Due to the lack of data available for the life cycle of a SFC for heating applications in general, the values applied as transfer coefficients are subject to uncertainties that may affect the results. As of 2018, there is very little statistical data available and more field studies are needed to assess the market for FC until 2050.

4 Conclusion

Aiming to examine how the implementation of mobile and stationary fuel cells will affect demand for critical raw materials and to what degree recycling presents a viable option for reducing the pressure on primary production, material flow analyses assessing the flows of platinum throughout the life cycles of both fuel cell vehicles and household CHP systems were conducted. As demonstrated, based on the developed scenarios neither the platinum requirements arising from a more widespread adoption of fuel cell vehicles nor the platinum demand from SFC household heating systems is likely to cause a depletion of PGM deposits in the near future. However, both technologies may increase the pressure on the already constricted platinum market, thus rendering this resource even more critical to European industries. While this effect is likely not felt from a wider adoption of SFC household CHP systems before 2050, significant additional demand for platinum from the adoption of fuel cell vehicles may arise within the coming decade. With regards to recycling, both technologies profit from the high recovery rates achievable for PGM provided the end-of-life products reach a state-of-the-art refining facility. The end-of-life supply chain that ensures PGM-containing end-of-life products arrive at a recycling facility can be considered relatively strong for SFC household heating applications. This is due to the fact that expert knowledge is required to install and uninstall the technology. Mobile fuel cell applications, such as fuel cell vehicles, however, have the drawback that markets exist outside of Europe as well and the products can easily be removed from the countries in which recycling facilities exist, causing a loss of recyclable material.

While only PEMFC were considered in this study, the SOFC technology is also of interest. A recycling chain does not yet exist for this technology, although recyclability is generally assumed to be high. Since yttrium oxide is used in the membranes of SOFC, further studies are necessary assessing the possible demand for this equally critical material as well as possibilities for recovering yttrium from end-of-life products.

5 Zusammenfassung

Aufgrund der geringen Emissionen in der Nutzungsphase zeigen sowohl mobile als auch stationäre Anwendungsbereiche für Brennstoffzellen vielversprechende Tendenzen, zukünftig an Relevanz zu gewinnen. Die für zwei Hauptanwendungsbereiche (Brennstoffzellenfahrzeuge und Blockheizkraftwerke) verwendeten Protonenaustauschmembran-Brennstoffzellen enthalten jedoch signifikante Mengen an Platin, welches von der Europäischen Union als kritischer Rohstoff eingestuft wird. Anhand einer Materialflussanalyse wird in diesem Beitrag untersucht, wie sich eine Einführung mobiler und stationärer Brennstoffzellenanwendungen auf den Bedarf an kritischen Rohstoffen auswirkt und inwiefern Recycling eine geeignete Strategie darstellt, um den Druck auf Primärquellen zu mindern. Es werden verschiedene Szenarien entwickelt, durch die gezeigt werden kann, dass eine großflächigere Einführung von Brennstoffzellenfahrzeugen und mit Brennstoffzellen betriebener Haushaltsblockheizkraftwerke in näherer Zukunft nicht zu einer Erschöpfung der Platinressourcen führen wird. Beide Technologien könnten jedoch den Druck auf den bereits jetzt eingeschränkten Platinmarkt erhöhen und so die Gefahr von Versorgungsengpässen für die europäische Industrie verstärken.

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