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ZINC AIR FUEL CELL VEHICLES

REVIEW OF DIFFERENT TECHNOLOGIES TO OBTAIN ZINC FROM ZINC OXIDE

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ABSTRACT

Several methods to recover zinc from zinc oxide are reviewed and are put in the context of Zinc-Air Fuel Cells (ZAFC) feasibility to power electric vehicles (EVs). These methods can be classified in two groups: electrowinning and carbothermal. Electrowinning methods are based on electrolysis, have been employed since decades in the conventional zinc production and are found to be very convenient for this application if the electricity needed is generated from renewable sources. Carbothermal methods are recent but have great potential, especially the SOLZINC process where biomass-based carbon feedstock is used to lower the operating temperature and reduce energy losses. Finally, three fuel reprocessing and distribution models are analyzed: centralized, distributed and in-car model. Three stages to implement ZAFC recharging systems are identified, starting with centralized model due to economies of scale and ending in in-car reprocessing model due to its full potential to compete with existing and future plug-in EVs.

AKNOWLEDGEMENT

Special thanks to Dr. Francisco Ruiz for his constant guidance and motivation in the realization of this project.

I would also like to show my gratitude to the rest of the great multidisciplinary team from which I learned a lot in the past months.

1. Background

The U.S. economy is strongly dependent on fossil fuels which are not renewable and, according to some studies, oil reserves will be depleted in the following decades [1]. In addition, fossil fuels combustion products such as SO_2, CO_2 or NO_x have a very negative impact on the environment and are responsible for the acceleration of the climate change.

Of all the energy consumption in 2009, almost 30% was consumed in transportation of goods and people and it relied mostly on fossil fuel sources (97%) [2]. Any effort in order to reduce the transportation dependence on fossil fuels will increase significantly the sustainability and security of the U.S. energy system, as well as reducing the environment pollution and mitigating the climate change.

In this context, finding new alternatives to fossil fuels to power vehicles is a real and urgent need. There are many car manufacturers that are developing new systems to use other sources of energy such as biofuels or electricity. Important efforts have been made to electrify vehicles and many of the results can be found in the current market and auto shows, mostly as plug-in hybrid vehicles powered by different kind of batteries.

A new approach to power electrical vehicles (EV) is being developed. Briefly, it consists of a Zinc-Air fuel cell system (ZAFC) that is fed with solid zinc pellets and potassium hydroxide electrolyte (KOH) and produces electricity and zinc oxide (ZnO). This product is later reduced to zinc in order to close the fuel cycle.

As discussed later, this system has a great potential to be introduced in the future EV market, but there are mainly two problems that need to be solved before:

- Separation of the ZnO from the electrolyte inside the car in order to transport the spent fuel in a safe and cost-effective way.
- Find the best method to reduce the ZnO in order to close the fuel cycle.

These problems are driving the research efforts of Dr. Francisco Ruiz and his team at the Illinois Institute of Technology (IIT).

In this paper, after justifying the use of ZAFCs for EV, how they operate and identifying the main problems that need to be solved, the main focus is in the different methods to reduce ZnO in order to recover the zinc and close the fuel cycle. Other team members are testing different devices to separate the ZnO from the electrolyte and will be published separately.

The main objective is to review and evaluate the potential and current status of each recovery method and lay solid foundations for future research.

Why Zinc-Air Fuel Cells?

As discussed earlier, many efforts have been made in order to reduce the dependence on fossil fuels for transportation. The most important alternatives that are being developed are biofuels, batteries and fuel cells. All of them have some advantages and disadvantages for their use in EV and are summarized in Table 1.

In the first place, biofuels have the great disadvantage that in order to produce enough fuel to power the huge amount of vehicles – which is increasing with time –, the land needed is very large. In countries where the land or the agricultural resources for food are scarce, this is not a promising solution. Furthermore, even if there were enough land to grow crops for both food and biofuels, the amount of water needed would be huge and not many countries have such water resources. Apart from this, biofuels are burned in internal combustion engines just as conventional fuels, limiting the efficiency (thermal combustion has lower maximum efficiency than electrochemical reactions). Some biofuels like liquid hydrocarbons from cellulosic biomass can be used for aircraft applications and may be a good alternative for that purpose [3]. Nevertheless, biofuels do not seem the best alternative to power vehicles.

Table 1. Advantages and disadvantages of different energy technologies.

Technology	Advantages	Disadvantages
Biofuels	- Reduce Greenhouse gas emissions - Can use existing infrastructure - Biodegradable - Renewable - Can be used for aircraft	- High capital cost - Require lots of land - Increase price of other agricultural products - Increase soil erosion and deforestation - Lots of water needed to grow plants - Limited to internal combustion efficiency
Batteries	- Closed system, no need to manipulate chemicals - High efficiency (no thermal combustion) - Eliminate pollutant emissions	- Must be plugged to the grid to recharge - Electric grid may be over-demanded - Use of fossil fuels in hybrid cars (higher mileage) - Long charge time (hours) - Low specific energy (Wh/kg) - Low energy density (Wh/liter) - Higher cost than fuel cells
Fuel Cells	- No need to be plugged to recharge it - Can be refueled quickly (minutes) - High specific energy (Wh/kg) - High energy density (Wh/liter) - Lower cost than batteries - High efficiency (no thermal combustion) - Eliminate pollutant emissions	- Open system, need to manipulate chemicals - Surrounding engineering systems - Cost of chemicals transportation and infrastructure to distribute them

In the second place, Battery electric Vehicles (BEV) have two main advantages that make them a very interesting alternative:

- Batteries are closed systems: there is no need for the user to manipulate the chemical substances and therefore they are safer than fuel cells.
- High efficiency: due to electrochemical reaction instead of thermal combustion.

Nevertheless, there are some disadvantages that are a serious barrier for their use in EV [4]:

- Low specific energy (Wh/kg) and energy density (Wh/liter): batteries are heavier and bigger than fuel cells + tank to store the same amount of energy. That traduces in heavier cars per mile driven and more space needed in the car to put the batteries.
- Must be combined with fossil fuels or biofuels (hybrid cars) in order to increase autonomy to at least 300 miles with a reasonable sized battery.
- BEV must be plugged into the electrical grid to recharge them: this is a great disadvantage because it takes from 4 to 8 hours to recharge them, decreasing the flexibility to use them.

Therefore, batteries may be an excellent solution for other applications but seem to be inconvenient for EV.

Finally, a fuel cell works like a battery but it has a significant difference: it is an opened system that only works in discharge mode. Therefore, in order to close the fuel cycle and get fresh fuel, it does not need to be plugged into the electric grid like batteries; it is done outside the system. For some applications this may be not significant or it may be a disadvantage, but for EV this can be a great advantage and increase significantly the autonomy and flexibility to use them. The main advantages of Fuel Cell Electric Vehicles (FCEV) are:

- FCEV do not need to be plugged into the grid: spent fuel is reprocessed outside the vehicle.
- The vehicle is recharged with fresh fuel in a time similar to conventional vehicles (less than 15 minutes).
- High specific energy (Wh/kg) and energy density (Wh/liter): unlike batteries, one or more of the reactants are stored outside the system and does not need to be carried in tanks, resulting in higher ranges for the same size and weight of the device. This is a key strength for their use in EV.

This approach to EV has some disadvantages too:

- Because it is an opened system, some dangerous chemicals (specially electrolyte) can be in contact with the user when manipulated. Some engineering solutions are needed to mitigate the risk.

- Extra cost to develop new infrastructures to transport fuel from production plants to refueling stations (centralized or distributed model will be discussed in Chapter4).
- Need to develop refueling systems to introduce the fresh fuel in the tank while recovering the spent fuel from the tank in a safe and quick way.
- Engineering systems required to guarantee a continuous and correct inlet and outlet flow.

In summary, fuel cells seem to have the greatest potential for their use in EV because those issues that have little or no room for improvement because are inherent to their nature (energy density, specific energy, etc.) are more favorable than batteries. Nevertheless, more research is needed to solve the challenges, which can be reduced to cost and engineering problems (auxiliary and refueling systems, distribution infrastructure, etc.).

Many types of fuel cells have been developed for different applications. The most popular is the Hydrogen Fuel Cell (HFC) and it has been used since decades ago, specially in spacecraft and stationary facilities, and recently in EVs [5]. Nevertheless, HFC has some disadvantages compared to ZAFC [6], [7]:

- Hydrogen is a high volatile gas and it is difficult and expensive to store the amount of hydrogen needed to drive for 300 miles. The more mileage, the more H2 and the more pressure you need to store it in a given volume. It is also difficult and dangerous to distribute it.
- Although H_2 is the most abundant element in the universe, it is mostly combined with other elements. Therefore, in order to obtain pure H_2, a lot of energy is needed and nowadays the most cost-effective way to do it is by steam reforming from natural gas, with important CO_2 emissions. There are other ways to obtain hydrogen like electrolysis but are not cost-effective at the moment.
- Electrodes need platinum (Pt) to catalyze hydrogen and oxygen electrochemical reactions and no other metal tested has been successful. This metal is very expensive and scarce and, if demand increases, prices will increase too (on July 15th, 2011 price was $1756 per oz. [8]). Actually, price volatility of platinum is very high and it is not convenient for an industry to depend on this kind of raw material (in 2008 the price ranged from $774 to $2,252 per oz. [9])

Although HFC research institutions are receiving funds from private companies and governments due to its popularity as a clean system, a lot of ignorance exists regarding the safety, overall efficiency and emissions of the process (well-to-wheel).

Therefore, more research is needed in order to find other kind of fuel cells that are more appropriate for EV applications. In this sense, the following advantages of ZAFC have been identified:

- Catalysts are made of non-precious metals such as MnO_2, Ag, Co_3O_4, $LaNiO_3$, etc. [10].
- High energy density (225 Wh/liter) and specific energy (110-330 Wh/kg) [7], [10], [11], [12].
- Zinc is the fourth most common element in the earth crust and is distributed all over the world [12]. This would decrease the dependence on unstable countries and secure a continuous supply at a fair price.
- Commercial methods to produce zinc from mines and waste products (galvanizer's ashes, tires, etc.) already exist.
- Spent fuel (ZnO) can be recycled to obtain fresh zinc pellets and close the fuel cycle. This is key for the success of ZAFC on the large scale and in Chapter 3 different technologies will be studied.
- Unlike most batteries that, in case of short circuit they discharge very quickly or produce gases as H_2 that may heat the battery in excess and begin a fire, ZAFC immediately stop discharging and, therefore, are safer [12].
- Quick recharge time (5-10 minutes) that increases flexibility to plan trips.

Particularly, ZAFC have some disadvantages that HFC do not have and need to be solved:

- ZnO tends to precipitate inside the fuel cell and reduces the active area of the electrodes. More research is needed to avoid this.
- In order to reduce transportation costs of spent fuel to the reprocessing plants, ZnO must be separated from electrolyte inside the car. Engineering systems are needed to do this in an efficient and continuous way.
- More research to find a method to reduce ZnO and obtain fresh zinc pellets in a large-scale and cost-effective way.

- Need of a new infrastructure to distribute and reprocess the solid ZnO and zinc.

In Chapter 3, different methods to reduce the ZnO are identified and discussed in order to determine which has the greatest potential for this application. In Chapter 4, centralized and distributed models are compared.

2. ZAFC operating principles

A Zinc-Air Fuel Cell works as shown in Figure 1 [13]:

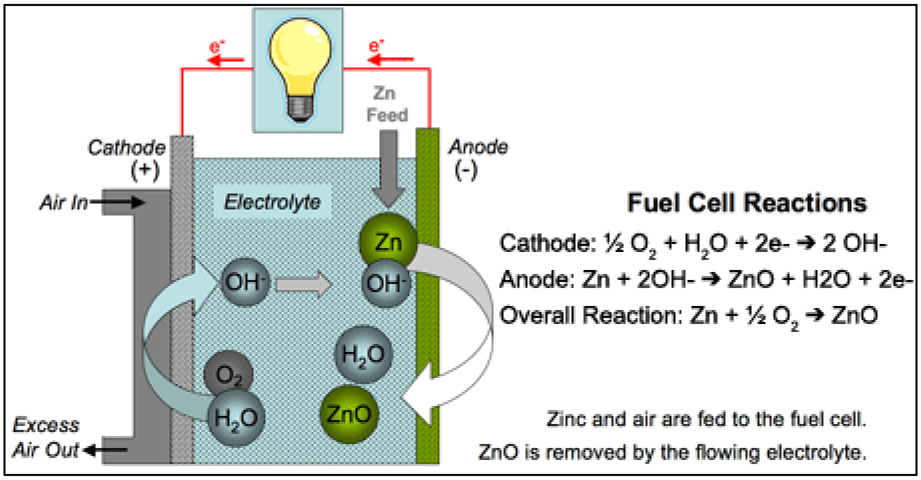

Figure 1. ZAFC electrode reactions.

At the cathode, oxygen reacts with the water of the electrolyte and is electrochemically reduced to hydroxide ions that travel through the electrolyte to the anode, where they react with Zn and produce ZnO, water and electrons. These electrons travel through an external circuit and produce electricity. The net reaction consumes zinc and oxygen and produces ZnO, heat and electrons.

The theoretical open circuit voltage (OCV) of a ZAFC defined by thermodynamics is 1.65V, but there are some activation losses that decrease the OCV to about 1.45V [14]. Apart from this, there are other kinds of losses when the fuel cell operates at different current densities. These losses can be identified in the polarization curve like the one shown in Figure 2, usually for the air cathode, which relates cell voltage and current density [11]:

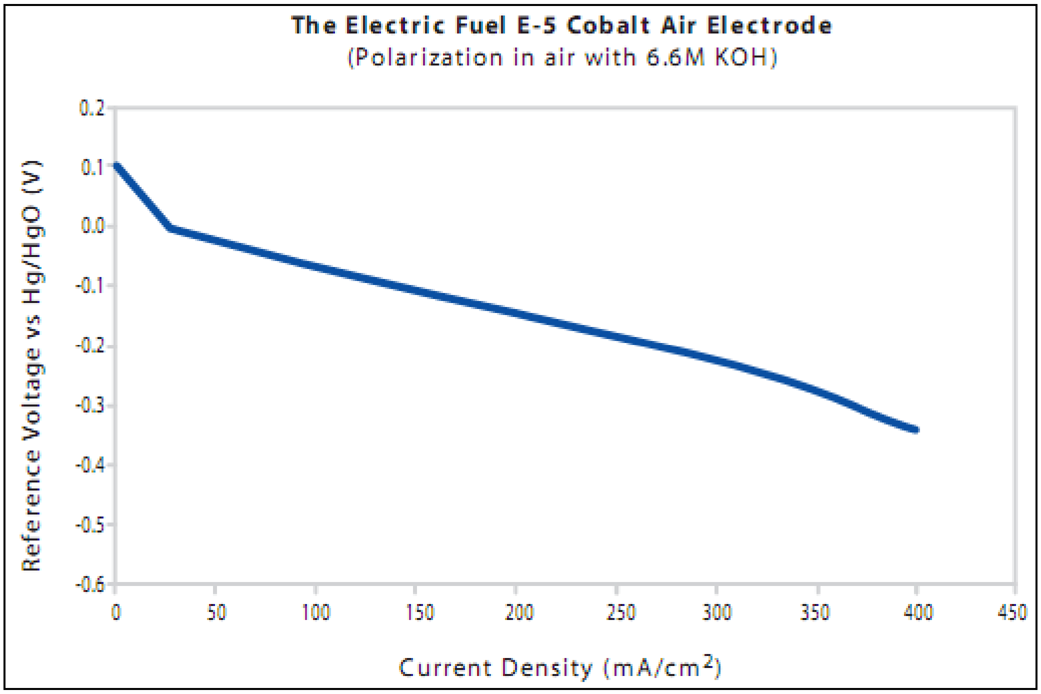

Figure 2. ZAFC polarization curve example.

There are 3 regions where different kinds of voltage losses (overpotential) predominate [15]:

- Activation losses at OCV and low current densities due to kinetic limitation of the reaction as deduced from Faraday's law. Reaction rate at the catalyst active surface is slower than the oxygen mass transport through the interphase, resulting in an accumulation of oxygen and voltage loss.

- Ohmic losses at mid current densities due to electric resistance of different conductive fuel cell components.

- Mass transport losses at high current densities due to the impossibility to provide the catalyst active surface with enough reactant. Oxygen diffusion through interphase is slower than the rate at which it is consumed in the catalyst surface, resulting in a voltage loss.

The limiting current density (i_L) is defined as the current density at which the mass transport is so slow compared to the reaction rate that the concentration of oxygen at the catalyst layer is zero. This is the maximum current density the fuel cell can produce.

One of the greatest advantages of this technology is that the spent fuel (ZnO) can be reduced to Zn through different methods in order to close the fuel cycle and, therefore, get a sustainable system as shown in Figure 3 [16]:

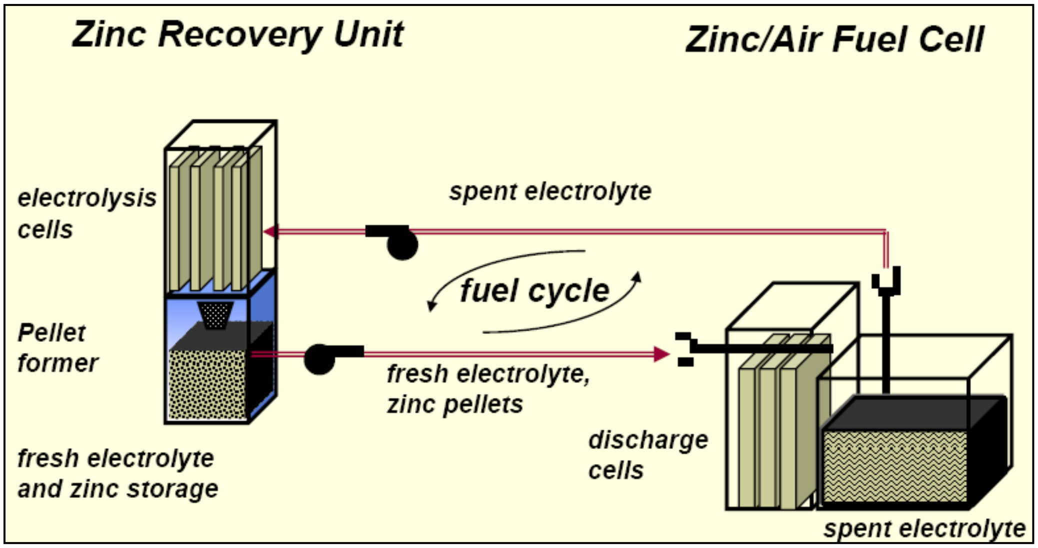

Figure 3. Fuel cycle in a Zinc-Air Fuel Cell system.

Basically, the zinc pellets are consumed in the ZAFC that produces electricity and ZnO (spent fuel), which is then reduced to zinc in order to form new pellets and distribute them to refueling stations.

The different methods to reduce the ZnO are explained in the following pages.

3. Zinc recovery methods

As explained before, once the zinc is consumed in the ZAFC, electricity and ZnO are obtained as products. This spent fuel needs to be reconverted to zinc metal in order to close the fuel cycle. In this chapter, different methods to reduce ZnO are discussed in detail in order to identify their potential for this application, their current status and further research objectives.

This step is considered very important for the success of a ZAFC economy for transportation because it has to be comparable in efficiency and cost to current fossil fuel systems in order to encourage governs and private companies to invest in this technology. If the new required infrastructure results to be very expensive and technically unfeasible, then other technologies will catch the attention of investors.

Historically, zinc is obtained from zinc ore, which can be found in minerals such as *blende*, *sphalerit*, *marmatite* or *calamine* and it contains 5-15% of zinc (as zinc sulfide, ZnS), so it needs to be concentrated.

In order to obtain zinc from zinc sulfide, the direct reaction would be the following [17]:

$$\mathrm{ZnS} + 2\,\mathrm{ZnO} \rightarrow 3\,\mathrm{Zn} + \mathrm{SO_2}$$

Nevertheless, this reaction is not favored and needs more than 1300 °C to continue. Therefore, conversion of zinc sulfide to zinc oxide (roasting), which is more reactive, is needed. This reaction is:

$$2\,\mathrm{ZnS} + 3\,\mathrm{O_2} \rightarrow 2\,\mathrm{ZnO} + 2\,\mathrm{SO_2} + 862\ \mathrm{kJ}$$

Sulfur dioxide is then treated to obtain sulfuric acid, which is later used in the process or can be sold to the market. After sulfur and other metals removal, zinc oxide is converted to zinc by either electrowinning (also called hydrometallurgical, with more than >90% of current zinc production) or pyrometallurgical methods at high temperatures.

In the case of ZAFCs, pure ZnO is obtained from the fuel cell and, therefore, roasting and sintering steps are not needed. Furthermore, pyrometallurgical methods are mostly employed when zinc ore contains big amounts of lead, which is not the case of ZAFC systems, so these methods will not be discussed. Nevertheless, carbothermal processes that use carbon at high temperatures to reduce ZnO are considered within pyrometallurgical techniques.

Finally, there are many methods to recover zinc from secondary sources such as waste products from galvanizer's ashes, brass foundries, tires, etc. but will not be studied because only pure ZnO treatments are considered in this project.

3.1. Electrowinning methods

The hydrometallurgical methods, also known as electrowinning or electrolysis, are the most common in zinc production.

Just as hydrogen is obtained from water, metals can be obtained from their oxides by electrolysis. When two electrodes are placed in a solution containing metal ions and an electric current is passed between them, the metal can be deposited on the negative electrode. In the recovery of most metals, oxygen is evolved from water at the positive electrode. An electrolyte, and a current density, is generally chosen that gives a dense, compact electro-deposit, and additives included in the electrolyte to further improve product quality [18].

There are different electrolysis methods that are explained below.

3.1.1. Zinc recovery by electrolysis with sulfuric acid

This is the most popular and established method where, after obtaining zinc oxide from zinc sulfate, it is electrochemically leached with sulfuric acid as follows [19]:

$$\mathrm{ZnO} + \mathrm{H_2SO_4} \rightarrow \mathrm{ZnSO_4} + \mathrm{H_2O}$$

After leaching, purification by cementation is done in order to obtain high purity zinc. Then, the electrolysis transforms zinc sulfate ($ZnSO_4$) into zinc metal and sulfuric acid, which is recirculated:

$$2\,ZnSO_4 + 2\,H_2O \rightarrow 2\,Zn + 2\,H_2SO_4 + O_2$$

The process flowsheet is shown in Figure 4:

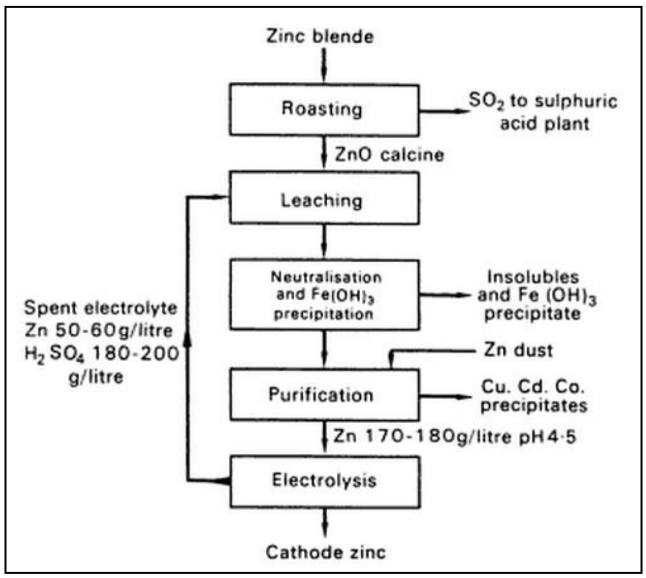

Figure 4. Electrowinning production of Zinc with sulfuric acid.

In the case of ZAFCs system for transportation, pure ZnO is obtained from the fuel cell and, therefore, only the leaching and electrolysis step are needed.

In the electrolysis, zinc metal is deposited on the negative electrode and oxygen is evolved, derived from water, at the positive electrode. The electrolyte typically contains 55 to 70 grams/liter of zinc as zinc sulfate and 150 to 200 g/l of sulfuric acid and is held at 35 to 38 °C (system needs to include a cooler to maintain constant temperature because electrochemical reactions produce 3.5 – 4.0 GJ/tonne of zinc produced). Small, controlled quantities of glue and antimony are added to the electrolyte to help form a smooth deposit. The positive electrode in zinc electrowinning is made from Pb-Ag alloys; oxygen evolution is promoted on these alloys and lead dissolution, which would contaminate the zinc product, is avoided. With this electrodes, a current density between 400 and 800 A/m^2 is employed (to optimize power), and this gives a cell voltage of 3.3 - 3.5 V/cell, an electrical energy consumption of 3.25 – 3.80 kWh/kg of zinc produced and a current efficiency of 90 – 95%. New materials for anodes were investigated by Huang et al. and claim to achieve better results with a Polyaniline anode (2.46 – 2.70 kWh/kg and 3.2 – 3.35 V), with a 20% energy savings [19], [20], [21].

The anode and cathode reactions are:

Anode: $$2OH^- - 2e^- \rightarrow 1/2O_2 + H_2O$$

Cathode: $$Zn^{2+} + 2e^- \rightarrow Zn(s)$$

Electrolysis with sulfuric acid is well known and is commercial, which is an advantage, but it is high energy intensive, which is a serious disadvantage for large scale applications. Another disadvantage is that it is designed to obtain zinc from zinc ore, which contains lots of impurities. In the case of ZAFC, where pure zinc oxide is produced, this process may not be optimized and other alternatives are explored in the following pages.

3.1.2. Zinc recovery by electrolysis at nickel electrodes

Zinc is recoverable from alkaline solutions of zinc oxide and potassium zincate by electrolysis between nickel electrodes, according to the reaction:

$$ZnO + H_2O + 2e^- \rightarrow Zn + 2OH^-$$

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

$$ZnO \rightarrow Zn + \frac{1}{2}O_2$$

The standard electrochemical potential for the overall reaction is 1.619 V. The oxygen is produced at the nickel anode, but the zinc particles that are formed do not adhere well to the cathode surface. Therefore, a simple bipolar electrolysis cell with sloped electrodes has been designed and is shown in Figure 5 [22]. As it can be seen, this configuration allows deposition of zinc particles on the upwards-facing surface of nickel plates, while downwards facing anodic surfaces sustains oxygen formation.

As oxygen gas bubbles are formed, they tend to move upwards and hit the anode surface, increasing the electrolyte convection and transport through the cell.

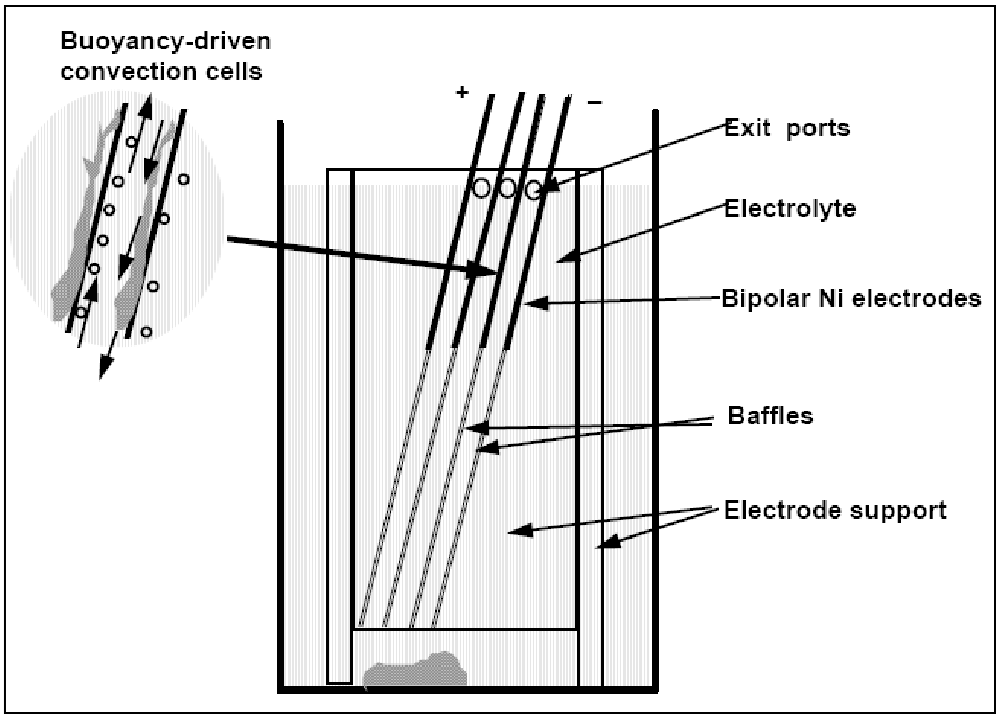

Figure 5. Electrolysis with nickel electrodes.

Two cells were operated at nearly constant voltage, while temperature and current were allowed to rise during electrolysis (Figure 6). The electrolyte contained 100 g-Zn/L dissolved in 12N KOH.

The operating conditions of a 2-cell electrolyzer with an electrode area of 25 cm2 were:

- 2-cell voltage was constant at 4.2 V.
- Current density < 1000 A/m2.

- Energy consumption was 1.8 kWh/kg.

The cell hardware is potentially inexpensive and therefore favors operation under low-rate, energy-efficient conditions.

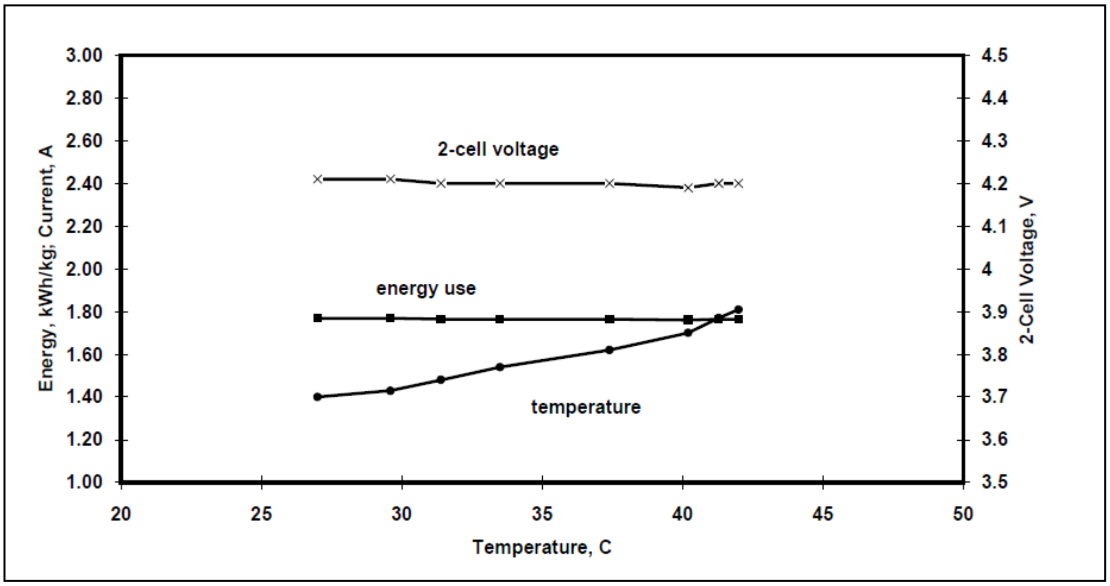

Figure 6. Voltage, energy use and temperature of a 2-cell electrolyzer with Ni electrodes.

Finally, zinc deposition in electrodes is well known because of its application to corrosion resistance of metals and this method seems to have a high potential because a simple and low-cost design can obtain high efficiencies and low energy consumption. Further research is needed in order to scale it up.

3.1.3. Zinc recovery using a hydrogen depolarized anode

In this method, a porous carbon anode catalyzed with Pt drives the hydrogen oxidation in order to recover zinc from ZnO [22]. The overall reaction is:

$$H_2 + ZnO \rightarrow H_2O + Zn \qquad E^0 = 0.39\ V$$

Hydrogen electrodes have been studied and developed since decades, specially for Hydrogen Fuel Cells in spacecraft applications, having more than 72,000 hours of lifetime.

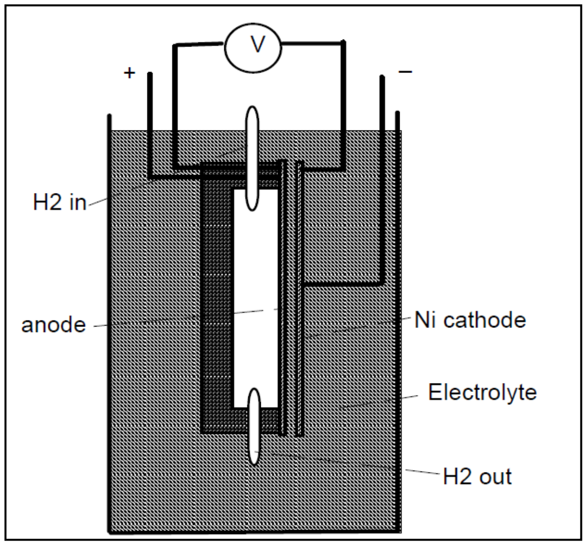

Figure 7. Hydrogen depolarized electrolyzer.

Cooper tested an electrolyzer with a hydrogen anode from Eagle-Picher (Ni/H2 No. 437) with an active area of 20 cm2. The cathode was a plate of oxidized nickel support at a distance of 6 mm from the anode so that electrolyte could flow in between by natural convection (Figure 7). The electrolyte contained 100 g-Zn/L dissolved in 12N KOH and the operating conditions were:

- Open circuit voltage (OCV) was 0.49 V (higher than theoretical 0.39 V due to losses).
- Temperature 28 °C.
- Current density < 1000 A/m2.
- Linear polarization curve that shows the resistance losses in the electrolyte (Figure 8).

When the gap between electrodes was reduced from 6 mm to 3 mm and the temperature risen to 40 °C, the resistance was reduced, natural convection was induced and a potential of 0.6 V and a current density of 800 A/m2 was achieved. More research is needed in order to scale it up because there are some issues like natural convection that are unlikely to work at large scale.

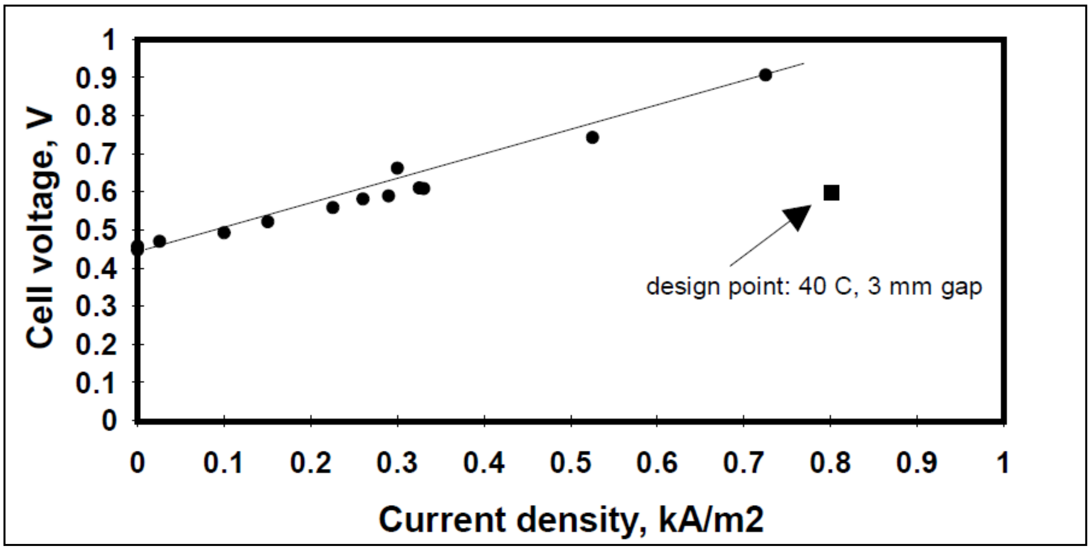

Figure 8. Polarization curve of a hydrogen depolarized electrolyzer.

The theoretical potential, compared to electrolysis at Ni electrodes (0.39 V vs. 1.619 V), allows a theoretical saving of 1.5 V, making this approach very interesting. Cooper compared the overall efficiency (natural gas to electricity) of the Ni electrolysis method explained before, the Hydrogen Fuel Cell (HFC) and the H_2/Zinc method. The energy flow is shown in Figure 9.

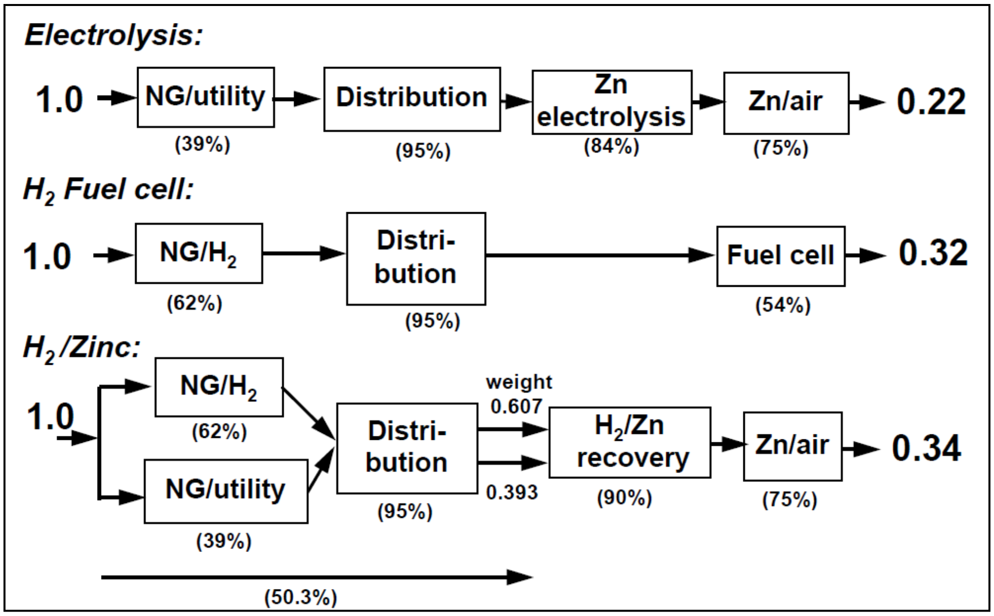

Figure 9. Comparison between classic electrolysis, HFC and H_2/Zinc electrolyzers in terms of overall efficiency.

As it can be seen, H_2/Zinc electrolyzers have an efficiency which is slightly higher than HFC and considerably higher than conventional electrolysis when the electricity comes from natural gas plants in all cases. Nevertheless, the effect of carbon emissions is not taken into account and the conventional electrolysis can be run completely with renewable electricity because it does not need hydrogen. For the other two methods, in order to produce hydrogen, the most cost-effective method that is currently available is by steam reforming from natural gas, which has a lot of CO_2 emissions. If in the future better and cleaner methods to produce hydrogen are developed, the H_2/Zinc method will need to be seriously considered.

Another big disadvantage of this technology is that current hydrogen electrodes use precious metals such as Pt to catalyze the electrochemical reduction of hydrogen. These metals are scarce, not well distributed and very expensive and this is a big problem for large scale applications. More research is needed in order to identify new catalysts based on abundant and cheap materials.

3.2. Carbothermal methods

Pyrometallurgical processes are based on the reduction of zinc oxide with carbon or carbon monoxide. To carry out this high temperatures are needed according to the reactions:

$$2ZnO + C \rightarrow 2Zn + CO$$
$$2ZnO + 2CO \rightarrow 2Zn + 2CO_2$$

As a consequence of the high temperatures required, zinc vapor is obtained and it has to be collected in a condenser. Some of the methods utilized are Horizontal Retort, Vertical Retort, Imperial Smelting and Electro thermal [19], which will not be explained because they are mostly employed when zinc sources contain big amounts of lead and other metals, which is not the case of spent fuel from ZAFC.

Nevertheless, there are other methods that also require heat (from the sun) and carbon to reduce zinc oxide and are called carbothermal methods. There are mainly three methods that use solar energy to obtain zinc from ZnO:

- Direct solar thermal dissociation of ZnO
- Carbothermic reduction of ZnO with solid carbon (SOLZINC process)
- Carbothermic reduction of ZnO with methane (SynMet process)

3.2.1. Thermal dissociation of ZnO

In this process, no reducing agents are needed and, therefore, very high temperatures are needed instead to drive the thermal dissociation of ZnO as follows [23], [24]:

$$2ZnO(s) \;\rightarrow\; 2Zn(g) \;+\; O_2(g)$$

One big advantage of this process is that it is completely independent of fossil fuels and only depends on solar radiation, making it a sustainable and environmentally friendly process to obtain zinc from zinc oxide. Another advantage of this technology is that zinc product contains all the energy of the products (zinc and oxygen) as opposed to other methods in which, apart from zinc, other gases such as CO, CO_2 or H_2 are formed.

A big disadvantage is that when operating at temperatures above 2000 K, the system becomes very inefficient because losses due to re-radiation increase with the fourth power of the absolute temperature (T^4). New materials to operate more efficiently at these temperatures are needed. Furthermore, because of high temperatures, zinc product is gaseous and needs to be condensed, reducing the overall efficiency unless the heat extracted is efficiently used somewhere else in the process.

Another big disadvantage that makes this process inefficient is that zinc and oxygen gases tend to recombine and form ZnO, reducing the efficiency even more. A very quick separation known as quenching has been proposed in order to avoid recombination.

A scheme of the solar reactor is shown in Figure 10 [24]:

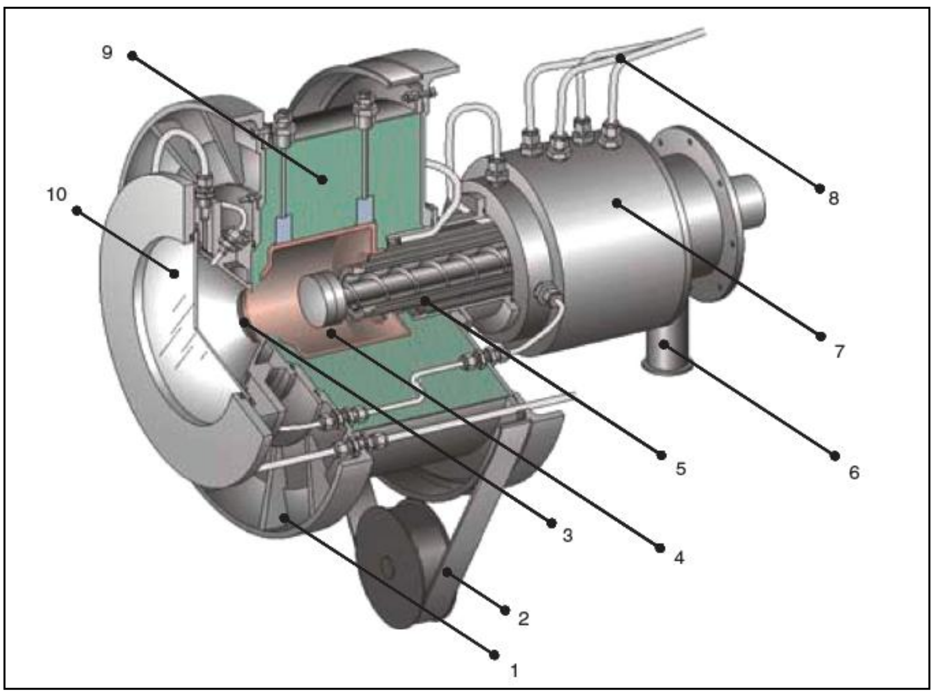

Figure 10. Solar reactor for thermal dissociation of ZnO.

A prototype of 10 kW is under development at Paul Scherrer Institut in Switzerland and at the University of Colorado.

This technology is very interesting because it does not rely on fossil fuels, but it has significant problems that are related to its own operating nature (mainly energy re-radiation and product recombination) and have little space for improvement. Its theoretical solar-to-fuel reactor efficiency is 40% assuming a 50% sensible and latent heat recovery and an incident solar concentration ratio of 500, at 2000 K [25].

In order to operate at lower temperatures and reduce the effects of re-radiation and recombination of products, a reducing agent is needed to drive the reaction. Carbonaceous materials such as solid carbon (SOLZINC process) or methane (SynMet process) have been proved to give good results.

3.2.2. SOLZINC process

In the SOLZINC process, ZnO reacts with solid carbon to obtain zinc and CO according to the following reaction:

$$ZnO(s) + C(s) \rightarrow Zn(g) + CO(g)$$

The temperature needed to drive this reaction at reasonable rates is about 1100 – 1200 °C, significantly lower than solar thermal dissociation [24]. As shown in Figure 11, the solar radiation is reflected in mirrors and concentrated in a solar tower and then it enters the solar reactor where the endothermic reduction of ZnO takes place, with emission of CO. The zinc obtained could be used to produce hydrogen in a water-splitting reactor or to produce electricity in a ZAFC, which is the case of interest of this project.

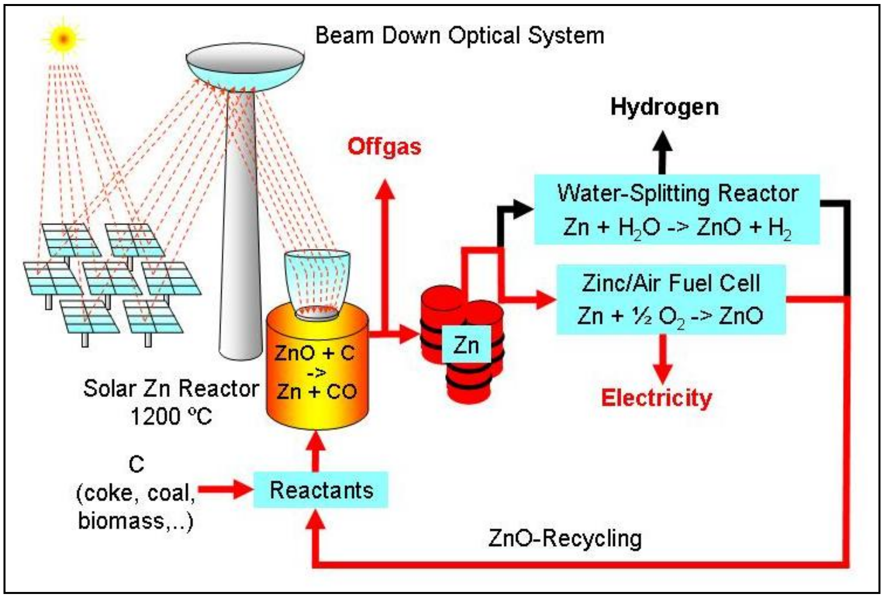

Figure 11. SOLZINC process integrated with electricity generation in a ZAFC.

A two-cavity batch solar reactor scheme is shown in Figure 12.

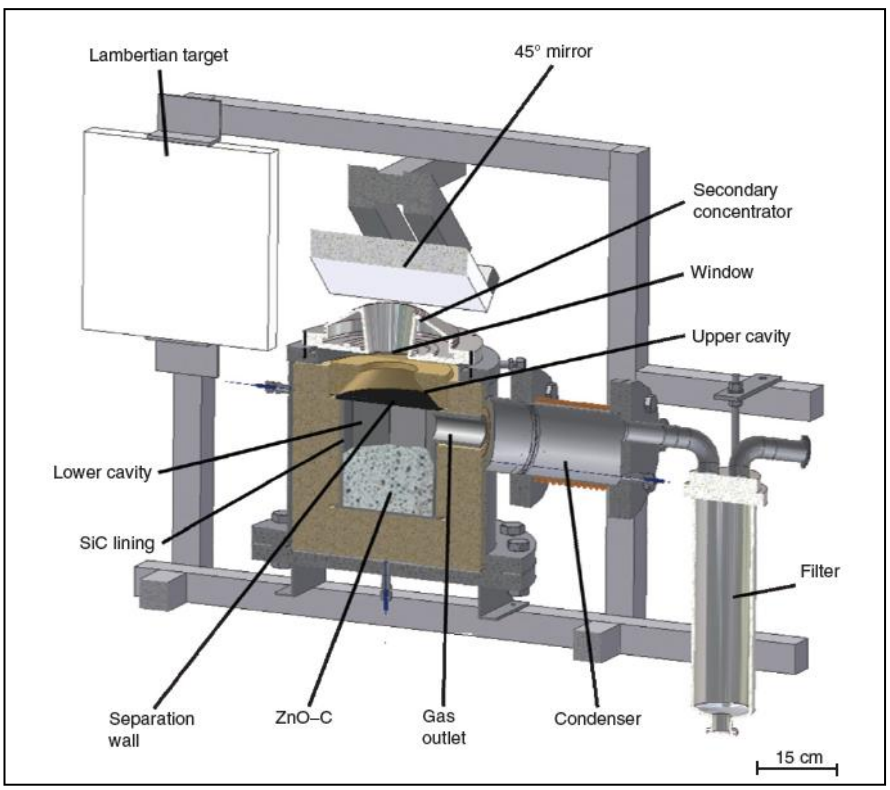

Figure 12. Two-cavity solar reactor for carbothermal reduction of ZnO (SOLZINC).

This reactor is designed to receive the concentrated solar radiation in the top from a solar tower as shown in Figure 12. This way, the solar reactor can be installed in the ground.

A mixture of solid ZnO and carbon particles receives indirectly the solar radiation through a thin wall that separates the upper and lower cavities. The reduction of ZnO takes place and it produces gaseous zinc and carbon monoxide. This mixture enters the condenser and the zinc sublimates to solid state in form of thin particles. The carbon monoxide is then separated with a ceramic filter to obtain pure zinc.

As carbon source, many materials are available, but biomass-based beech charcoal has been proved to react faster and at lower temperatures, as shown in the thermogravimetry in Figure 13. Because this material is biomass-based, SOLZINC process results to be almost carbon neutral and definitely better than electrowinning methods that use electricity produced from non-renewable sources.

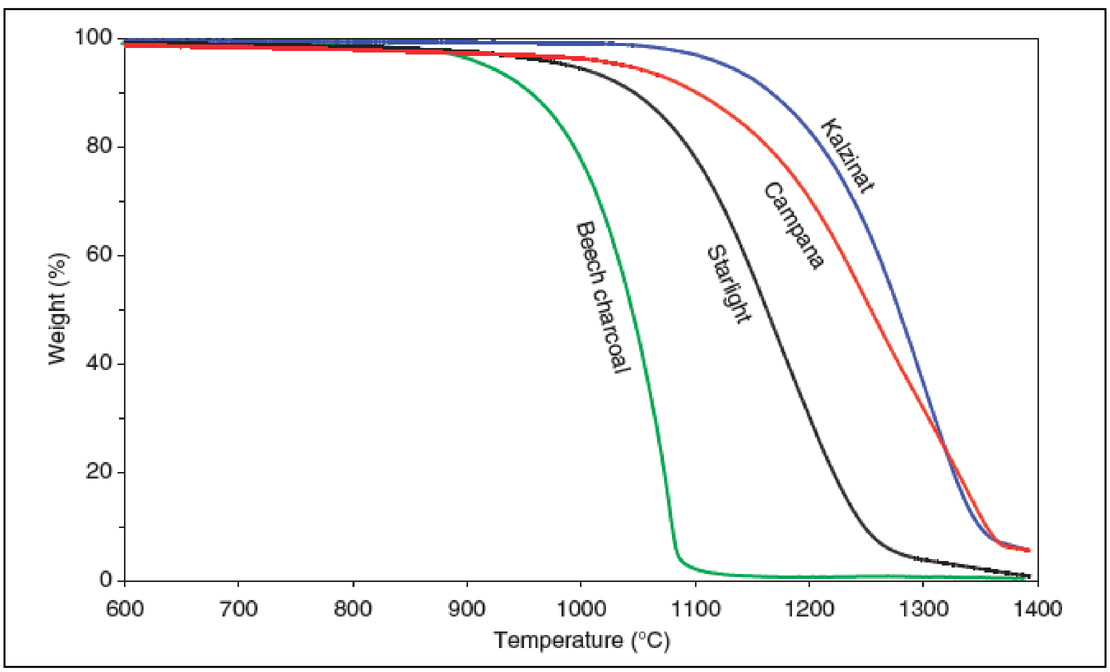

Figure 13. Thermogravimetric results to compare different carbon sources.

Two kinds of efficiencies were identified by Steinfeld et al. to describe a 300kW pilot plant that produces 50 kg of zinc per hour:

- Thermal efficiency defined as the ratio of the energy absorbed to the total solar energy input and resulted to be ≈30%.
- Process efficiency defined as the ratio of the lower heating values (LHV) of produced zinc and CO to the sum of the solar energy input and the heating value of the carbon consumed. It turned to be also ≈30%.

Reasons for the losses are mainly reflection of the concentrated sunlight at the quartz window and re-radiation through the aperture and walls. Efficiencies around 50% can be achieved with optimized reactor design.

Apart from the 300 kW tested pilot plant and based on the results obtained, a 50 MW and 30 MW commercial plants were designed and are expected to produce 1.7 and 10 tonnes of zinc per hour, respectively. The solar-to -fuel efficiencies are expected to be 57% for the 5MW plant and 64% for the 30MW [26].

It has been estimated that the cost of producing electricity through this method in addition to a ZAFC system is about 0.15 €/kWh and 0.30-0.40 €/kWh for a 30 MW and a 5 MW solar plant, respectively.

The main advantages of this technology are that it uses renewable solar energy to produce zinc and a biomass carbon feedstock so that the process is carbon-neutral and works at lower temperatures. Nevertheless, some challenges exist regarding better design to minimize energy losses and perform a quick and efficient separation and condensation of zinc.

3.2.3. SynMet process

This process is similar to the SOLZINC, but instead of using carbon as a reducing agent, methane is used and the reaction yields zinc and syngas as follows:

$$ZnO(s) + CH_4(g) \rightarrow Zn(g) + 2\,H_2(g) + CO(g)$$

This reaction takes place at temperatures above 1075 °C. The reactor design for a 5 kW pilot plant is different compared to the SOLZINC reactor and operates continuously (Figure 14)[27]. The chemical conversion for zinc oxide was 100% and for methane 96%. The thermal efficiency was about 15-22%, but may be increased in further large scale applications by recovering heat from the products.

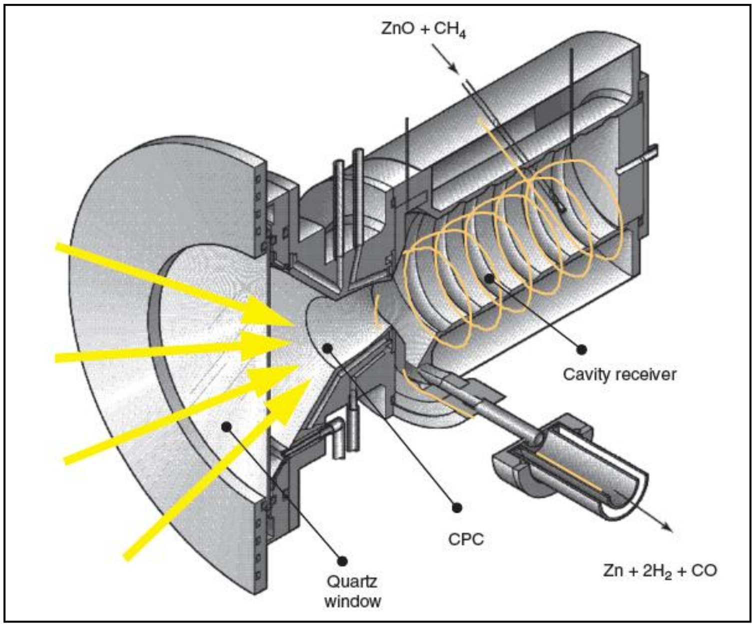

Figure 14. Solar reactor to produce zinc and syngas (SynMet process).

In this process, the zinc product is also gaseous and needs to be cooled down quickly in the exit to separate it from the syngas.

The main advantage of this process is that it allows building a very flexible energetic scheme where zinc is produced to store energy and use it later in ZAFC to generate electricity or to produce hydrogen and then electricity in a HFC. The syngas produced can be used in existing combined cycle plants to produce electricity, it can be used to make other products such as methanol or it can be used to produce pure hydrogen also. This system is shown in Figure 15 [24].

It has the same disadvantages as the SOLZINC process and also that it uses a fossil-fuel like methane to drive the reaction. Nevertheless, this approach produces much less CO_2 per kWh of electricity produced than the conventional methods to obtain syngas or hydrogen.

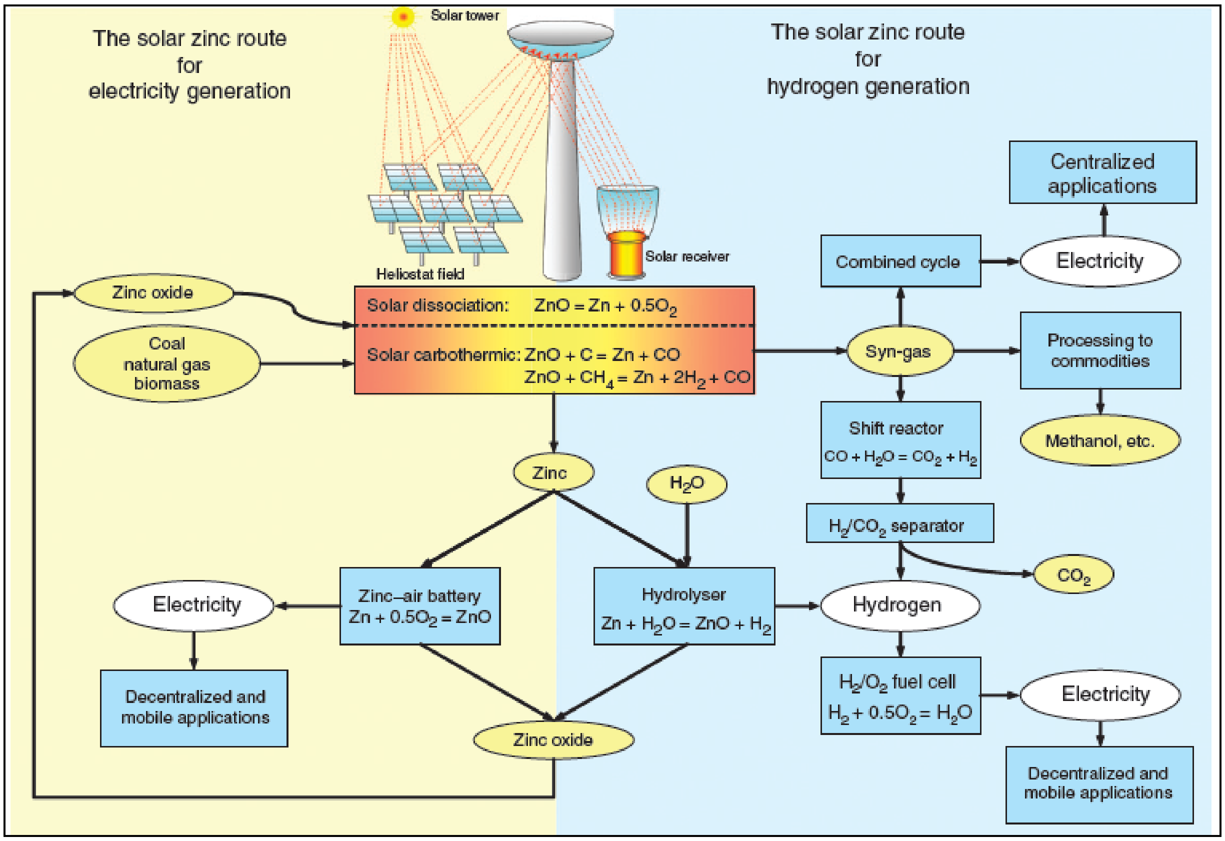

Figure 15. Solar fuels based on ZnO/Zn cycle.

In Table 2 the three solar methods studied are compared. Regarding the operating temperature, the worst case is the thermal dissociation because it needs more energy and the losses due to re-radiation are higher. Nevertheless, the zinc produced in the thermal dissociation contains all the energy of the products, which is not the case of the ZINCSOL and the SynMet processes because they produce CO and syngas, respectively.

Table 2. Comparision between solar thermal dissociation of ZnO, SOLZINC and SynMet processes.

Process	*$ZnO \rightarrow Zn + 1/2\ O_2$*	*$ZnO + C \rightarrow Zn + CO$*	*$ZnO + CH_4 \rightarrow Zn + CO + 2H_2$*
		SOLZINC	SynMet
$T(\Delta G = 0)$	2335 K	1220 K	1110 K
ΔH^0	460 kJ mol^{-1}	350 kJ mol^{-1}	447 kJ mol^{-1}
$HV_{Zn}/(HV_{Zn} + HV_{off\text{-}gas})$	1	0.56	0.32
Development status	Lab	Pilot	Lab
Challenge level	Large, fundamental issues	Medium, just engineering issues	Medium, engineering issues

HV = heating value

Regarding the current status, the SOLZINC is the most developed with a 300 kW pilot plant already tested and a 5 MW and 30 MW commercial plants designed.

Finally, there is little space for improvement for the thermal dissociation because the main challenges are related to fundamental issues such re-radiation losses due to high operating temperatures or recombination of zinc and oxygen in the exit.

4. Fuel reprocessing and distribution models

Once the different methods to recover zinc from zinc oxide have been reviewed, it is very important to think about the refueling model. There are three different possibilities:

- Centralized reprocessing of zinc in big plants
- Distributed reprocessing of zinc in small units
- In-car reprocessing of zinc (plug-in vehicle)

Each one of the models has some advantages and disadvantages that need to be deeply studied in order to build the most efficient refueling system that is possible. This has been identified as a basic need for the success of ZAFC because some existing and new alternative technologies do not have the need to build a new refueling infrastructure or the expenses are lower. Actually, the Chicago Booth School of Business (University of Chicago), in cooperation with Dr. Ruiz's project team, identified the strengths and weaknesses of ZAFC for their use in EVs and also determined the research opportunities for our team at IIT. These are explained in the study presentation in the APPENDIX at the end of this report.

In the following sections the three models are analyzed.

4.1. Centralized reprocessing model

In this model, reprocessing of spent fuel is done in one big plant (via electrowinning or carbothermal methods) as shown in Figure 16. The spent fuel is sucked out from the fuel tanks in the refueling stations and taken to the reprocessing plant where zinc is recovered and redistributed to the refueling stations or at-home refueling units. The transportation of fresh and spent fuel should be done by the most cost-effective way (truck, train or ship) depending on each region. Actually, the reprocessing plants should be located near a big river or an important railroad because it is cheaper than using trucks.

This infrastructure model has some advantages:

- Easy and quick to implement because few plants are needed in a very big region.
- Low transportation and reprocessing costs due to economy of scale.
- Easily scalable to bigger markets.
- Reprocessing can be done via carbothermal methods because these kind of plants need big space to install enough solar reflectors.

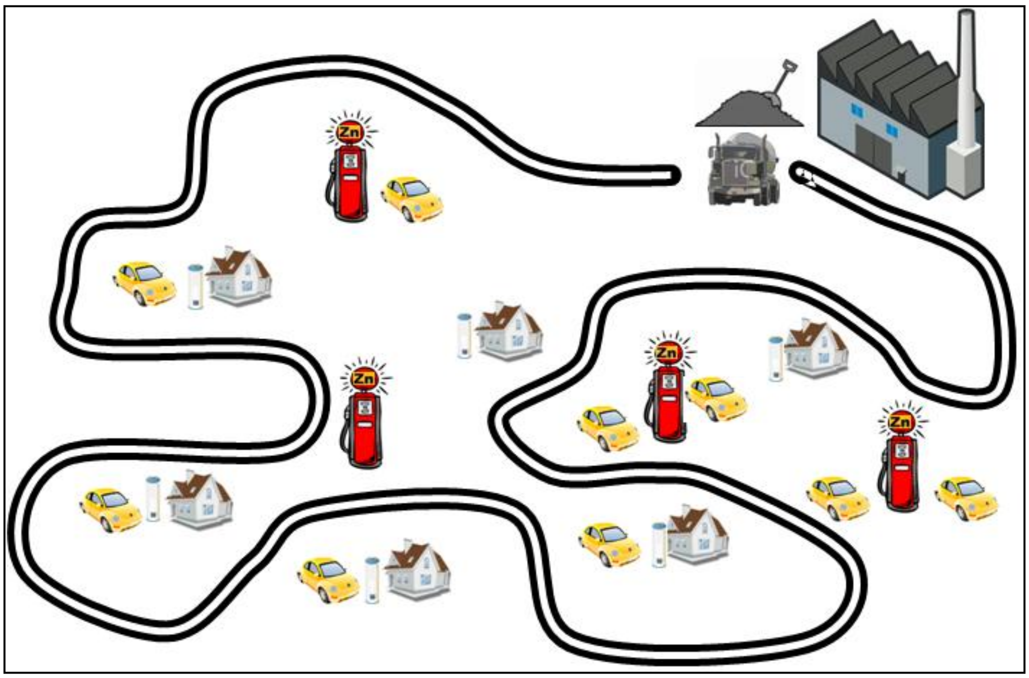

Figure 16. Centralized reprocessing model.

Nevertheless, there are some barriers or disadvantages of this model:

- Need of filtration and separation systems to transport spent fuel in a cost-effective way (transport ZnO without electrolyte).
- Development of external refueling systems to introduce fresh fuel in the tank while sucking out the spent fuel.
- Requires storage tanks at the refueling points in order to guarantee fuel disposal at any moment, just as in current refueling stations.

- Transportation of fuel is not “green” because big vehicles such as trucks, trains or ships are difficult to power with renewable fuels or electricity.

Therefore, this model is adequate in a first stage of ZAFC implementation because costs are low and in regions that are near the main transportation channels.

4.2. Distributed reprocessing model

In this model reprocessing is done via recharging systems that are located on-site (at-home or refueling stations), as shown in Figure 17.

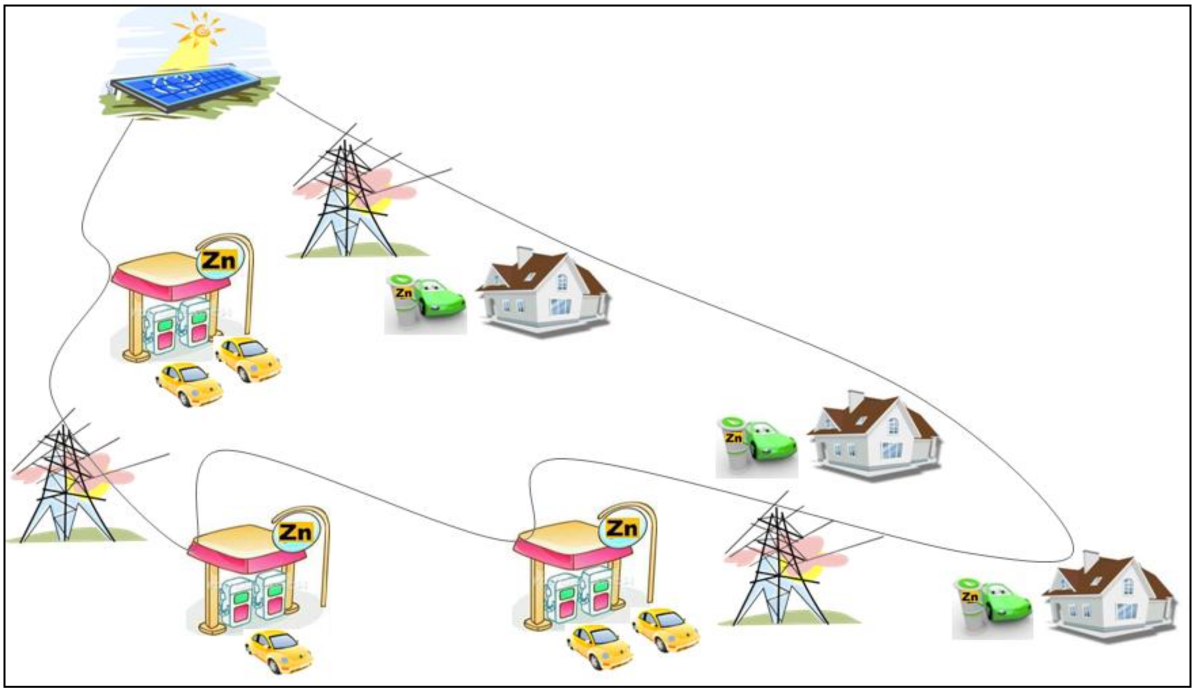

Figure 17. Distributed reprocessing model.

This configuration has some advantages:

- Eliminates the need of distribution infrastructure and the carbon emissions related to it.
- No need of storage tanks so that refueling units can be located both in the houses or refueling stations.
- High flexibility because of short recharging time (minutes).

- Existing electric grid and compatible with distributed electricity generation such as solar panels.

The disadvantages are the following:

- Need of separation and filtration of ZnO because electrolyzers use acidic solutions as electrolyte, not alkaline solutions like KOH.
- Need of engineering systems to ensure safe manipulation of electrolyte.
- Need to develop efficient electrochemical recharging units.
- Development of external refueling systems to introduce fresh fuel in the tank while sucking out the spent fuel.
- Not compatible with carbothermal methods, only electrochemical methods available.
- Electricity must be produced from renewable sources in order to result in a sustainable and clean system.
- Recharging units must be priced similar to existing plug-in technologies.

Therefore, this model is adequate for a second stage where required refueling and reprocessing systems are cost-effective and safe, and electric grid is completely integrated with renewable energy systems.

4.3. In-car reprocessing model

In this model, reprocessing is done with electrochemical devices inside the car, so that external recharging units are not required and existing EV recharging infrastructure is compatible. The result is a plug-in car but with shorter recharging time than conventional electric vehicles (minutes instead of hours). Another advantage is that there is no need to manipulate the electrolyte or any other dangerous substance because all is done internally. Again, there are no carbon emissions due to transportation of fuel.

Nevertheless, there are some barriers that make this approach difficult to implement with existing technologies:

- Need of filtration and separation techniques just as in the other models because the electrolysis is done in an acidic environment.
- Need of smaller and inexpensive equipment in order to have enough space to include reprocessing units. This gives the car manufacturers less flexibility to design them.
- High dependence on electrical grid so that it may be over-demanded.

Therefore, this model seems to be the most expensive with the current technology but has a great potential when cost-effective engineering systems are available and electrical grid is upgraded to handle with the increase of demand in a sustainable and clean way.

5. Conclusions and future research

In this project, different technologies to recover zinc from ZnO have been studied with the objective to identify their potential, current status and lay the foundations for future research. The conclusions are summarized in Table 3. Basically, in the short term, electrolysis with sulfuric acid should be employed because it is a mature technology and the process is optimized. Nevertheless, it is a high energy consumption process so investment is needed to develop other promising solutions such as SOLZINC or SynMet processes because of their potential to build an integrated zinc and hydrogen production system with solar energy that would give more flexibility in the long-term.

Regarding the reprocessing and distribution models, the centralized model would be the first stage due to its low cost and flexibility with respect to the recovery method (big solar carbothermal facilities can also be integrated). If electrowinning is the reprocessing method chosen, it should be located close to renewable energy parks such as wind farms or solar facilities in order to store energy in zinc fuel when the electricity generation exceeds the demand.

The second stage would be the distributed model where electrolysis is done in small units located at residential or commercial points, saving a lot of money in transportation costs and, therefore, reducing carbon emissions.

Finally, the third stage to implement and make ZAFC cars competent with conventional EV is the in-car reprocessing of spent fuel. If there is a big advance in the following years in the development of small and cheap electrolyzers, in addition to massive renewable-sourced electricity, the first and second stages may be omitted.

Table 3. Potential, current status and challenges of different zinc recovery methods.

Technology	Potential	Status	Future research	Comments
Electrolysis with sulfuric acid	Mature technology	Commercial (conventional zinc production)	- Optimize process for pure ZnO feed	- High energy consumption - High current efficiency - Electricity should be clean
Electrolysis at Ni electrodes	High	Lab testing	- Large scale tests - Zinc deposition in Ni electrodes	- Low energy consumption - High current efficiency - Electricity should be clean
Electrolysis at H_2 depolirized anode	Moderate (H_2 needed)	Lab testing	- Find clean and cheap ways to produce H_2 - Forced natural convection at large scale - Explore non-precious catalysts for oxygen evolution	- Higher well-to-wheel efficiency - Savings of 1.5 V - Electricity should be clean
Thermal dissociation	Low	Lab scale (10 kW)	- Improve solar radiation absorption - Quick zinc separation - Heat recovery from products	- Theoretical efficiency of 40% not feasible due to re-radiation and recombination losses - Not compatible with distributed and in-car model
SOLZINC process	High	300 kW tested 5 - 30 MW designed	- Improve solar radiation absorption - Quick zinc separation - Heat recovery from products	- Biomass-based carbon source - Efficiency up to 64% in 30 MW plant - Not compatible with distributed and in-car model
SynMet process	Moderate (CH_4 needed)	Lab scale (5 kW)	- Improve solar radiation absorption - Quick zinc separation - Heat recovery from products	- Fossil-fuel carbon source (CH_4) - Thermal efficiency up to 22% with possibility to increase - Flexibility to integrate with HFC systems, cogeneration and commodities production - Not compatible with distributed and in-car model

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APPENDIX

IIT Labs
Zinc-Air Fuel Cell Vehicle Project

Chicago Booth School of Business
Cleantech Lab (34706)

Heather Birdsall
Zach Drawbaugh
Kentaro Nagai
Ryan Newman

The University of Chicago Booth School of Business

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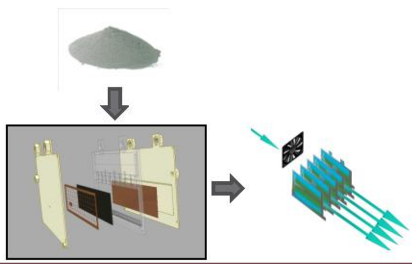
Introduction

What is a Zinc-Air Fuel Cell?

Electro-chemical battery powered by oxidizing zinc with oxygen from the air

- High energy density, Cheap material
- Mature technology: Developed in 1960s by US military and academia
- Current Usage: Grid storage and Button cells used for hearing aids or watches



Project Scope

Basic Questions
- Is there a Market Opportunity for Zinc-Air Fuel Cell Vehicles?
- How can IIT Lab fit into the space?

Stakeholders
- IIT Labs: Paco Ruiz and Grad Students
- Exelon (Funder)
- Zinc Air Inc.

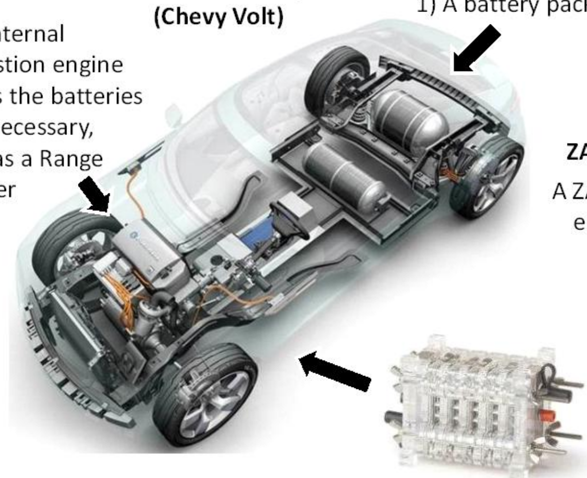
Scope of Solution Space
- Domestic Markets
- Battery
- Vehicle Components
- Infrastructure

An Illustration of a ZAFC Vehicle

Traditional "Series hybrid" (Chevy Volt)

1) A battery pack powers the vehicle

2) An internal combustion engine charges the batteries when necessary, acting as a Range Extender



ZAFV "Series hybrid"

A ZAFV replaces the IC engine, charging the batteries and functioning as the Range Extender

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Executive Summary

There will be a market in the US for electric vehicles
Key Drivers: National security, Environmental awareness, Price of Oil, Government incentives
There are unmet needs in current EV offerings
Unmet needs: Range, Quick Charging Time, Price, Familiarity with Technology, Brand Trust, Infrastructure and Convenience, Larger Vehicle Options
Zinc-air Fuel Cell Vehicles (ZAFVs) are a viable option for mass deployment of "electric vehicles"
ZAFV strengths: Longer range, Quick Charging Time, Lower price, Larger Vehicle Options
There are serious challenges ahead for ZAFVs
Technology Development: Filtering System, Recharging System
Investment: Infrastructure and Logistics
Competition: Lithium-Ion and Other Battery Technologies, Recharging Stations
Three potential models exist for ZAFVs Refueling Infrastructure
Centralized Smelting
Distributed Electro-chemical Charging
In-Car Electro-chemical Charging + Refueling
Business opportunities for IIT
Oxidized Zinc Filtration: License technology to interested automotive partners
Electro-chemical recharging
-Manufacture and sell or operate stations
-License technology to manufacturers
-Form partnership with manufacturers

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The EV market in the United States is growing

	Early Majority 2010 - 2020	Mainstream
Market Size	1.3M potential	Reach sales of 6-8M electric vehicles/year
Profile	67% Male HHI: $118K 100 Miles/Week 88% have garage & power Urban & Suburban	Possible Segmentation: Average American Profile: 51% Female Location: Urban / Suburban / Rural Purpose: Commuting / Shopping / Traveling / Multi-Purpose Primary / Secondary Vehicle
Drivers	1. Reliability 2. Purchase Price 3. Convenience 4. Cost to Recharge 5. Environmental Credibility 6. Government Incentives	1. Purchase Price 2. Reliability / Brand Recognition 3. Lifetime Cost 4. Battery Technology Development

2020 Prediction

Conservative: 1.9%; 285K units

Likely: 3.1%; 465K units

Aggressive: 5.6%; 840K units

Source: Selling Green in Today's Market. GfK Research. October 2010.
Electric Cars: Implications for the Automotive Industry and Beyond. May 2010.
Electrifying Cars: How Three Industries will Evolve. McKinsey Quarterly, Number 3. 2009.
Appendix: Market Research

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Current EVs do not meet all the needs of consumers

Range	70% of people surveyed would expect an electric vehicle to travel 300 miles before they would consider purchasing one
Length of Charging Time	An EV will take between 30 minutes to 8 hours to charge
Price	73% of people expect to pay between $8K and $35K for an electric vehicle
Familiarity with Technology	Customers will be hesitant to use technologies that they are not educated on or aware of
Brand Trust	Toyota, Honda, and Ford have brand-permission in this space due in part to the green brand equity they built through hybrid sales
Infrastructure and convenience	The infrastructure for charging the batteries of a large number of electrified vehicles isn't in place, nor is the industry tooled to produce them on a mass scale.

Source: Electric Cars: Implications for the Automotive Industry and Beyond. May 2010.
Electrifying Cars: How Three Industries will Evolve. McKinsey Quarterly, Number 3. 2009.

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ZAFVs satisfy several currently unmet needs

Other potential benefits to ZAFVs exist

	ZAFV	EV	ICE
Range	300 miles	50 – 160 miles	300+ miles
Time to Refuel	~ 5 minutes	30 mins – 8 hrs	~ 5 minutes
Price (MSRP)	$27,500	$30,000 - $67,000	$18,000 and up

Additional Benefits:

	ZAFV	EV	ICE
National Security	Zinc mined in the US	Instability in Lithium regions	Instability in oil regions
Vehicle Variety	Not constrained by ZAFC technology	Low due to battery constraints	High
Environmental Impact	Low	Low	High

Source: Electric Cars: Implications for the Automotive Industry and Beyond. May 2010.
Electrifying Cars: How Three Industries will Evolve. McKinsey Quarterly, Number 3. 2009.

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Challenges for ZAFV Ecosystem

Internal challenges are within IIT Labs' control

	Internal Challenges	External Challenges
Battery and Vehicle	• Filtering System • Control System • Weight • Power • Partnership with manufacturer Technology Development Required	• Commercialization of new technologies (ex. Lithium-Air, Lithium-Sulfur) • Lithium-Ion Battery Pricing (Learning Curve) • Consumer's Brand Recognition
Infrastructure	• Development of Refueling System • Development of Zinc Distribution Model • Significant Amount of Investment • Partnership with manufacturer, developer, retailer **Refueling Model Development Required!**	• Consumer adoption of current EV technologies • Major EV infrastructure build-out and investment (charging stations, battery swap stations) External Factor Analysis Required

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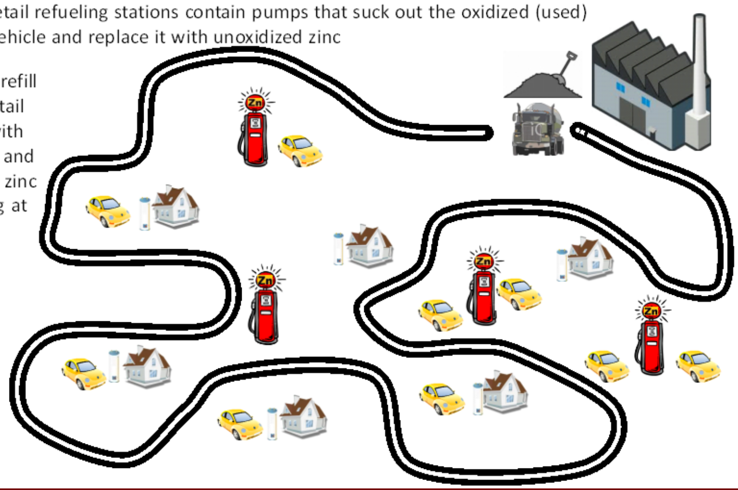
Model 1: Centralized Charging - Description

- All reprocessing is done centrally via smelting by a zinc processor
- Unoxidized zinc is formed into tiny pellets and delivered to home storage tanks (phase 1) and also to retail "refueling" stations (phase 2)
- At-home and retail refueling stations contain pumps that suck out the oxidized (used) zinc from the vehicle and replace it with unoxidized zinc
- Delivery trucks refill at home and retail storage tanks with unoxidized zinc and collect oxidized zinc for reprocessing at the plant



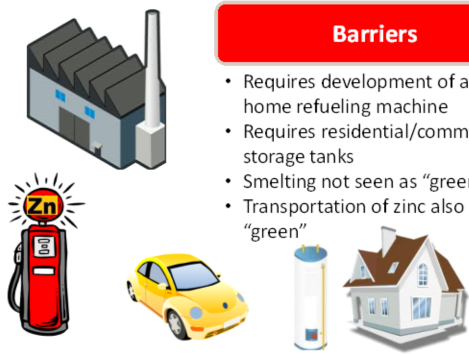
Model 1: Centralized Charging - Breakdown

New Technologies Required!

- Development of delivery infrastructure
- Filtration systems
- External refueling systems

Advantages

- **Quickly and easily deployed**
- Inexpensive to reprocess
- Inexpensive to transport (~$20/ton)
- Requires little "new" technology
- Could be scaled to accommodate virtually any # of vehicles in a given market
- Same delivery infrastructure could service residential and commercial storage tanks

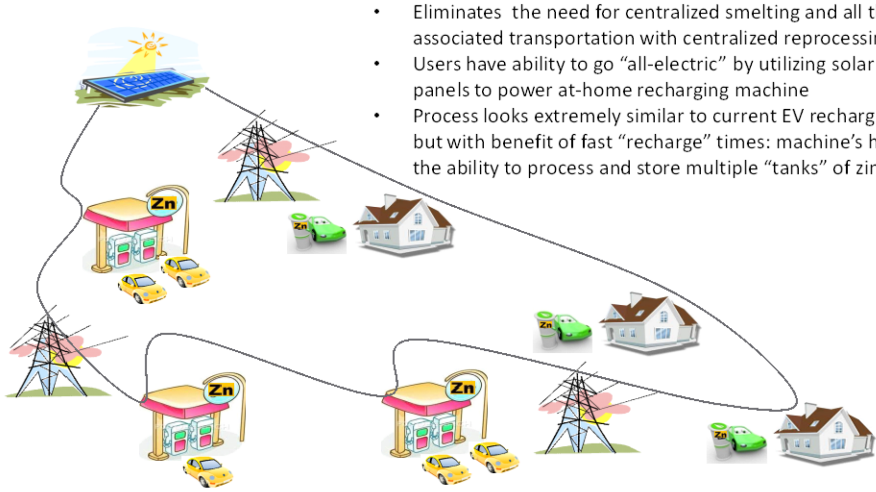


Barriers

- Requires development of at home refueling machine
- Requires residential/commercial storage tanks
- Smelting not seen as "green"
- Transportation of zinc also not "green"

Model 2: Distributed Charging - Description

- Reprocessing and refueling done "on-site" via at-home or retail charging stations using electro-chemical recharging process
- Eliminates the need for centralized smelting and all the associated transportation with centralized reprocessing
- Users have ability to go "all-electric" by utilizing solar panels to power at-home recharging machine
- Process looks extremely similar to current EV recharging but with benefit of fast "recharge" times: machine's have the ability to process and store multiple "tanks" of zinc



Model 2: Distributed Charging - Breakdown

New Technologies Required!

- Filtration systems
- External refueling systems
- External recharging systems

Advantages

- **Reduces or eliminates need for delivery infrastructure**
- **Minimizes distribution costs**
- Carbon emissions limited to recharging process
- Recharging costs reduced to price of required electricity
- Eliminates need for at-home storage
- Process resembles current EV recharging so consumers will have familiarity

Barriers

- **Requires development of at home refueling as well as electro-chemical recharging**
- Machine must be priced equivalent to EV chargers
- Must keep electrolyte away from consumers
- Must use minimal electricity to keep per-mile costs competitive with EVs

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Model 3: In-Car Charging Description

- Electro-chemical recharging process takes place inside the vehicle via an internal charger
- Vehicle would plug into an electrical outlet to power the internal charger
- Closed loop system eliminates any potential consumer contact with toxic electrolyte
- Vehicle could internally recharge or refuel via external refueling options outlined previously

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Model 3: In-Car Charging - Breakdown

New Technologies Required!

- Filtration systems
- External refueling systems
- External recharging systems
- In-car charger

Advantages

- **Like an EV, in-car charging would allow the driver to charge car at any outlet**
- Could utilize any available EV charging infrastructure
- Closed-loop system would eliminate any potential exposure to toxic electrolyte
- Charging costs limited to price of electricity (i.e. no raw material purchases required)
- Carbon emissions limited to recharging process

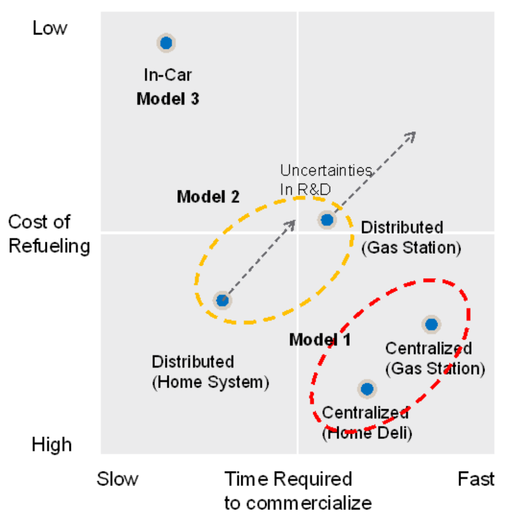
Barriers

- **Requires development of inexpensive and small-scale charger capable of fitting in a vehicle**
- Unless car also has ability to "refuel", drivers will still be faced with range anxiety issues

Analysis of Options

Three step market entry and expansion strategy

Commercialization and Refueling Cost

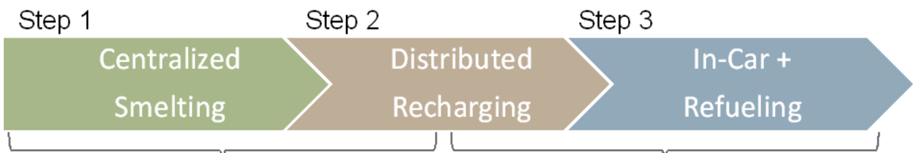


Other Criteria

	Model 1 Centralized Smelting	**Model 2** Distributed Recharging	**Model 3** In-Car + Refueling
Research & Develop-ment	Easy	Hard	Very Hard
Logistics Complexity	High	Moderate	Moderate
Target Segment	Limited	Moderate	Wide
Break-even Point	Low	High	High
Economy of Scale	Moderate	High	High
Co-existence with EV ecosystem	Low	Low	High
Step	**1**	**2**	**3**

Factors Determining Charging Infrastructure Roll-out

Faster Technology Development could lead to bypassing Step 1



Factor	Recharging Technology Development • Drastic technology development in distributed recharging system that decreases manufacturing cost	EV Market Expansion • Rapid expansion of EV market along with the fast deployment of recharging infrastructure
IIT Strategy	Rapid market entry with distributed recharging system. Omit Step 1.	Co-existence with other EVs. Focus on Step 2 and Step 3

Risks in Transition Model:

1) Large R&D investment in every steps
2) Customer adoption to each technology

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Milestones for Execution

IIT needs to play an integral role in developing ancillary technology

Priorities for Tech/Biz Development

	Requirements	Availability of external resources	IIT R&D Space	Phase
Vehicle	Filtering System		X	
	Control System	X		
	Power	X		
Infra	Zinc Distribution Model	X	(X)	Model 1
	Electro-Chemical Charging System		X	Model 2
	In-Car Charging System		X	Model 3

Revenue Generation Options

	Option 1 Minimum Requirements	Option 2 Build Own Business
R&D	X	X
Patent / IP	X	X
Facilitation	(X)	X
Manufacturing		(X)
Distribution		X
Marketing		X

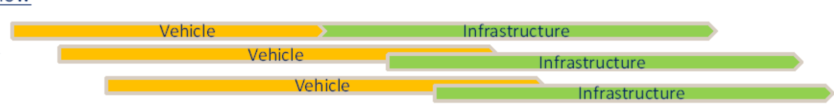
Trade-off: Commitment vs Mark-up

Execution Flow

Research

Fundraising

Partnership



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Conclusion and Recommendations

- Consumer ZAFC-powered vehicles are a viable alternative to EVs/Plug-in Hybrids and business opportunities exist in the space.
  - Partnership(s) with Toyota, Honda, and/or Ford will increase competitive advantage of ZAFV
- Zinc-Air Fuel Cells are being developed but our research shows a lack of development in the required support systems and infrastructure
  - Filter system is crucial to success of ZAFV
  - Infrastructure development is crucial to success of ZAFV

IIT Technology Development Opportunities

Opportunity #1: Zinc Filtration

- Required for any consumer refueling model!
- Filtering oxidized zinc particles from electrolyte allows for safe extraction of zinc from the vehicle for electro-chemical reprocessing or centralized smelting
- Enables recharging of "partial" tanks

Opportunity #2: Electro-chemical charging

Inexpensive and safe electro-chemical recharging:

- Facilitates quicker consumer adoption of ZAFC vehicles
- Reduces carbon emissions by eliminating the need for zinc transportation network
- Reduces cost and complexity of refueling
- Provides "unlimited" range through deployment of retail charging machines

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Next Steps for IIT

Success in technology development leads to future funding and partnerships

Immediate (1 year)	• Identify preferred development opportunity (s) ▪ Zinc Filtration, Electro-chemical recharging, or both • Develop feasibility plan and calculate detailed funding requirements • Arrange a working partnership with ZAFC manufacturer to gain access to a test ZAFC ▪ Zinc Air, Inc., Leo Motors, ReVolt, etc
Long Term (3 years)	• Assemble complete team • Obtain funding ▪ Corporate sponsorships (Exelon, etc) ▪ DOE Grants ▪ ARPA-E ▪ Clean Energy Trust ▪ Angel Investors/Venture Capital

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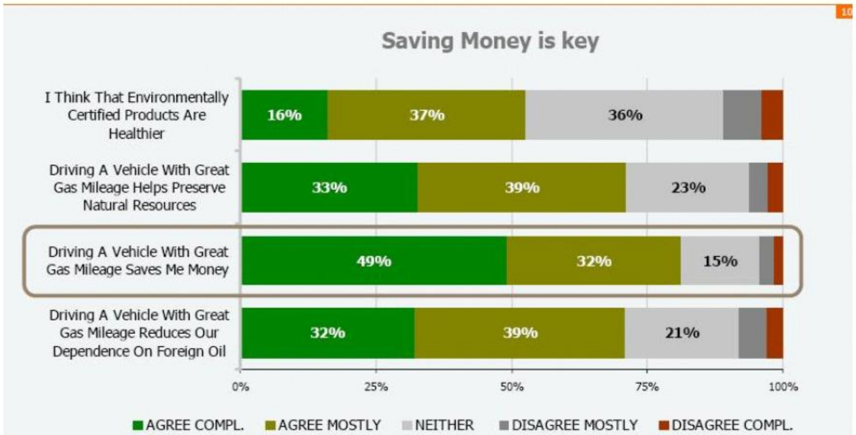
Appendix 1: Price is important to consumers

The main reason for driving a vehicle with high MPG is…
…the *other Green* --- $$$!



Selling Green in Today's Market. GfK Research. October 2010

Appendix 2: Electric Vehicles are not conveniant

Different fuel types are seen to have different tradeoffs
Gas is convenient, but Electricity is clean and safe

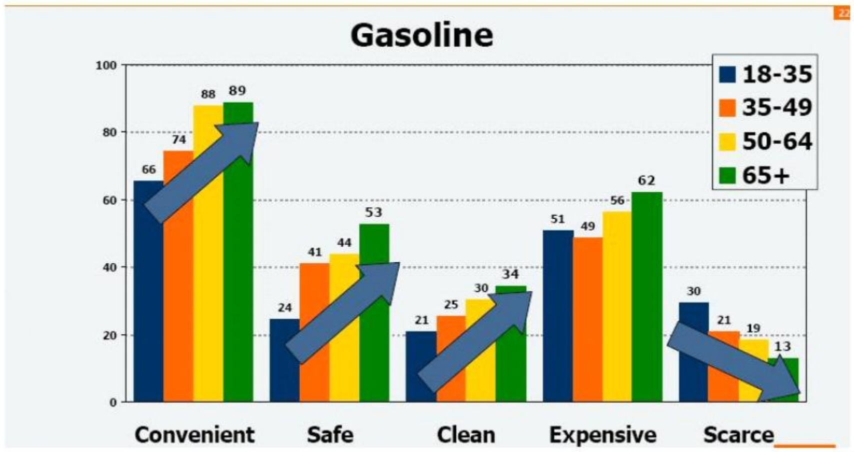
Gasoline is Convenient, but Expensive

Electricity is Clean & Safe, but not convenient

Selling Green in Today's Market. GfK Research. October 2010

Appendix 3: Younger demographics are less positive about gasoline than their older counterparts

Different fuel types are seen to have different tradeoffs
Younger consumers are less positive about gasoline in general



Selling Green in Today's Market. GfK Research. October 2010

Appendix 4: Competitors: Battery (Short Term)
Tech. improvement/overproduction decreasing Li-ion price

Main U.S. Vehicle Battery Manufacturers

Company	Year	Revenue	Capacity	Partnership	Government Support	Price
A123	2001-	$91,049K	24,000 EV/y (end of 2010)	BMW Chrysler Fisker GM Renault Better Place	DOE: $25B loan State of Michigan: $10B grant	$650/kwh (2009)
Ener1	1985- Li-ion: 2005-	$34,800K	12,000 EV/y (Oct, 2010)	Think Volvo	DOE: $118.5M grant	$450/kwh (2012)
Johnson Controls	1885- Li-ion: ?	$28,497M Li-ion: ?	N.A.	N.A.	DOE: $299M grant	$350/kwh (2020)

Existence of Competitive foreign manufacturers (capacity/size)

Rapid growth in revenue / capacity.
Demand/Supply balance?

LEAF: Automotive Energy Supply (NEC/Nissan JV)
BYD: own manufacturing facilities

Sharp battery Cost decrease!

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Appendix 5: Competitors: Battery (Long Term)
New technologies are trying to cut into Li-ion's dominance

Long-term Drivers

Tech. Develop-ment

•Intensive Governmental support on Research and Development

Government Backed R&Ds

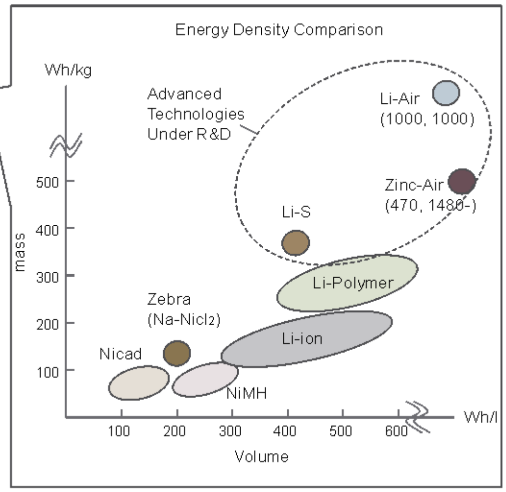
Company	Technology
24M	Lithium
Planar Energy	Lithium
Sion Power	Lithium-Sulfur
Poly Plus	Lithium-Air
Revolt	Zinc-Air

Lithium Production

•Limited Potential?
•Underdeveloped in countries with high political risk (Bolivia, etc.)

Lithium Production and Reserves

	Production(08)	Reserves
World	25,400 ton	9,900 K ton
Chile+Bolivia		9,000 K ton



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Appendix 6: Competitors: Vehicle
Most firms release EV in 2010, but ranges are limited

Vehicle	Battery	Price	Speed	Range	Charging	Release	Remarks
Plug-in Prius (Toyota)	Li-ion	$33,000-	112mph	12 miles (+gas:-)	1.5hrs (220V)	2010	PHEV
Volt (GM)	Li-ion	$41,000-	100mph	25-50 miles (+ gas: 350miles)	4 hrs (240V)	2010	PHEV
Leaf (Nissan)	Li-ion	$33,000-	87mph	100 miles	7hrs (240V) 30min (Lv. 3)	2010	
Roadster (Tesla)	Li-ion	$109,000-	>130mph	250 miles	60min (LV.3?)	2008	2-seater
E6 (BYD)	Li-ion	$40,000-	87mph	205 miles	6hrs (220V)	2010	China
TH!NK City (TH!NK)	Li-ion Zebra	$38,000-	68.3mph	100miles	Li-ion 8hrs Zebra 7hrs(80%)	2008	Best seller EV Only in EU

Capacity? Price Range $25K-$40K Evs: 100-250 miles 6-8 hours with Level 2

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Appendix 7: Vehicle Cost Comparison

Vehicle	Prius PHV	Chevy Volt	Nissan Leaf	Tesla S	Fisker Karma	ZAFC
Battery Pack / ZAFC	$2600	$8000	$9000	$28000		
kW/h	*5.2*	*16*	*24*	*42-70*	*22.6*	
$ per kW/h	*$500*	*$500*	*$375*	*$660*		
ICE / Secondary battery		$2000	NR	NR		
Sticker Price	$33,000	$41,000	$32,780	$57,400	$87,900	
Home Charger	$2200	$2000	$2200	NR	$3000	
US Tax Credit	-$2917	-$7500	-$7500	-$7500	-$7500	
Price to Consumer	$32,283	$35,500	$27,480	$52,900	$83,400	
Battery weight (in lbs)	330	400	660	1200		
Total weight (in lbs)	3400	3500	3500	3825	5000	

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Appendix 8: EV Charging Market

EV Infrastructure Companies	Type	Level	Output Charge	Time	Location/Market
Coloumb Technologies ChargePoint	Residential	I II	2 kW 7.2 kW	14 hours 4 hours	Metropolitan areas throughout the United States and Europe : Los Angeles, San Diego, San Francisco, New York, Dallas, Austin, Houston, Miami, D.C., Detroit, Chicago
	B2B/Fleets	I II III	2 kW 7.2 kw 50 kW	14 hours 4 hours 30 minutes	
	Curbside / Business	I II III	2 kW 7.2 kW 50 kW	14 hours 4 hours 30 minutes	
GE WattStation™	Residential	I		4-8 hours	Residential in 2011, Curbside in late 2010
	Curbside / Business	I		4-8 hours	
better place	Battery Switch Station	N/A	N/A	2 minutes	Australia, China, Denmark, Israel, Japan, Canada, US: California (bridge metro areas), Hawaii (battery swap)
	Public and Residential Charge Spots	II		4-8 hours	
Ecotality Blink	Residential	II			EV Project, 15, 085 stations by 12/31/12: AZ, CA, OR, TN, TX, WA, D.C.
	Commercial	II III	30-60 kW	< 30 minutes	

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Competitive Advantage of ZAFVs

Half of EV limitations solved by ZAFV

Range	70% of people surveyed would expect an electric vehicle to travel 300 miles before they would consider purchasing one
Length of Charging Time	Current EVs take 30 minutes to 8 hours to charge
Price	73% of people expect to pay between \$8K and \$35K for an electric vehicle

Source: Electric Cars: Implications for the Automotive Industry and Beyond. May 2010.
Electrifying Cars: How Three Industries will Evolve. McKinsey Quarterly, Number 3. 2009.

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Summary of Refueling Models

Each model is scalable for any amount of vehicle concentration

		Re-Oxidizing				Refueling		
Model	Phase	Vehicle	Home	Gas Station	Factory	Home	Gas Station	Electrical Outlet
Model 1: Centralized Charging	1				X	X		
	2				X	X	X	
Model 2: Distributed Electro-Chemical Recharging	1		X			X		
	2		X	X		X	X	
Model 3: In-Car Charging + Refueling		X	X	X		X	X	X

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