Future Vehicles Will Be Driven by Electricity, But Not as You Think

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The debate on what will be the car of the future has been ongoing for many years now and only seems to intensify. Throughout the years, there have been many views, some would say hypes, on what would be the most likely candidate technology enabling sustainable transportation. The early 1990s saw the end of the large-scale fleet trials of methanol-fueled vehicles, followed by the introduction of electric vehicles (EVs) some years later. The new millennium started off with high hopes for the hydrogen fuel cell vehicle (FCV). Homogeneous charge compression ignition (HCCI) engines were going to save the day a few years later, combining the best features of the gasoline and diesel engine cycles. In recent years, the pace seems to have picked up: around 2007, biofuels were in the picture (mainly ethanol); in 2009, EVs again came on stage, this time joined by plug-in hybrids and range extended EVs. Most recently, with increased shale gas development, natural gas vehicles (NGVs) have been on the rise.

Looking at the situation today, it seems very difficult to pick the most likely candidate to emerge from this multitude of options. The very fact there are so many alternatives is easily explained given the complexity of the problem. We are looking for transportation to decrease energy use, greenhouse gas emissions, and pollutant emissions, and increase energy security, while remaining affordable and not compromising on driving range, interior space, and comfort. Furthermore, what is frequently forgotten is that any alternative has to be scalable. Not only have we passed the 1 billion vehicle mark in 2010, but also, with present growth rates, this number is expected to double by the early 2020s, with the BRICS[1] countries taking the lion's share of this growth. As we will discuss below, scalability has a number of implications.

[1]The acronym for five major emerging national economies: Brazil, Russia, India, China, and South Africa.

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So, given the above, what we set out to answer here is whether we can find out what would be the energy carrier for transportation in the future, and which type of powertrain will be used. We will test every solution we come up with at least by two criteria: sustainability and scalability.

I. WHICH ENERGY SOURCE?

The first question is how we will power our future society in general. This has to be answered before we narrow this down to transportation. Luckily, Abbott has done an excellent job in addressing this question [1]. Comparing the potential of the energy sources at our disposal to the worldwide energy needs, only solar energy is shown to have the potential to deliver these energy demands sustainably, with enough excess capacity to cope with the increasing energy demands. Other sources can contribute (e.g., wind and hydro), but as these are in fact just very diluted forms of solar energy, their potential is at least two orders of magnitude lower than solar. In a sustainable society, the base energy demand thus has to be met by solar energy.

II. WHICH TECHNOLOGY TO CAPTURE THE ENERGY?

Different possibilities exist to capture solar energy and convert it into an energy carrier. To select the most appropriate technology, we have to look at the scale of the task. Again, following Abbott's reasoning [1], solar thermal plants emerge as the method that is most easily scaled up. With solar thermal, solar energy is concentrated to generate heat, which is used to produce steam, which in turn drives a steam turbine coupled to a generator to produce electricity. The scalability stems from the relative simplicity of the technology and from the fact that it does not rely on raw materials of which reserves are limited (in contrast to photovoltaic).

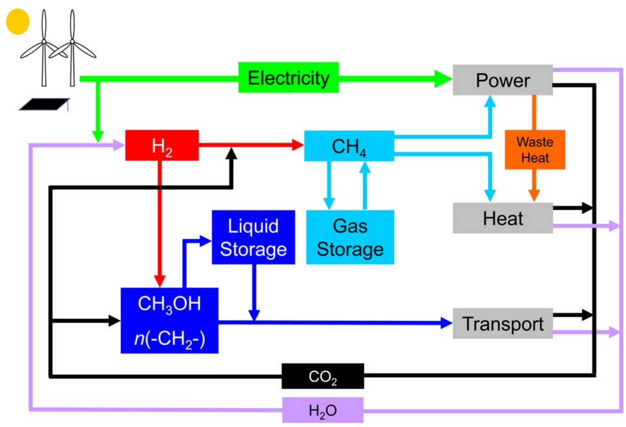

Fig. 1. An integrated power, heat, and transport system combining renewable sources with synthesized fuels [7].

III. WHICH ENERGY BUFFER?

As reflected by a special issue of the PROCEEDINGS OF THE IEEE [2], the intermittency of renewable energy sources such as solar, hydro, and wind is a major hurdle to their large-scale use. The potential of these sources can only fully be used when there is a solution for buffering energy on a massive scale. One of the possibilities is to use hydrogen as an energy buffer.[2] The most sustainable and scalable way for hydrogen production is to split water using alkaline electrolysis, when there is an excess of renewable energy. Converting hydrogen back to electricity can then cover the period when energy demand outweighs renewable energy production or the hydrogen can serve directly or indirectly (see below) as an energy carrier for transportation.

IV. WHICH ENERGY CARRIER TO POWER TRANSPORTATION, AND WHICH POWERTRAIN?

As our sustainable society drafted above relies on solar energy to produce electricity, and buffers the energy using hydrogen, the most logical way of providing transportation means seems to rely on one of these two energy carriers to power vehicles. Going to battery electric vehicles or hydrogen fuel cell vehicles thus seems like the way to go. Again, the scale of the problem has to be taken into account, in this case the total number of vehicles worldwide. If we want to equip such a number of vehicles with batteries or fuel cells, to power electric drives, once more we come up against the limits formed by the reserves of certain raw materials needed. Ramping up the production of electric vehicles, for instance, has been reported to be constrained, if not by lithium resources [1] then by the availability of certain rare earth elements [3]. Hydrogen fuel cells need platinum as catalyst material, again preventing them from being a truly scalable option.

From the viewpoint of scalability, the tried and tested internal combustion engine (ICE) is a much more sustainable alternative. ICEs are made from abundantly available and moreover recyclable materials. Consequently, they are also cheap to produce.[3] Of course, in a sustainable

[2]Other options are detailed in the special issue dedicated to energy storage [2].

[3]In fact, as they rely on a cyclic process in which peak temperatures only occur during a brief part of the cycle, with cooling periods in between, they can use cheap materials and still get up to high peak temperatures, allowing relatively high peak efficiencies. Thus, they are probably the technology with the best ratio of energy efficiency to cost.

society they can no longer rely on oil derivatives as fuel. However, ICEs have the added advantage of being fuel flexible and can also operate on, for example, hydrogen.

Hydrogen turns out to be an attractive engine fuel, as its properties allow hydrogen engines to be operated at peak efficiencies not too far off of practical fuel cell systems [4], with ultralow emissions, for a fraction of the cost of fuel cell systems and with proven reliability. Naturally, upon combustion, water vapor is formed so that a sustainable cycle results. As vehicles powered by hydrogen ICEs seem to meet the sustainability and scalability criteria, Abbott advanced them as the solution for meeting our transportation demands [1].

However, keep in mind that we are talking about transportation here, i.e., vehicles, having to carry the energy onboard. Thus, next to sustainability and scalability, energy density is crucial and, unfortunately, this is where hydrogen fails. Even when highly pressurized (with 700 bar—10.000 psi—tanks currently most favored) or liquefied (requiring temperatures below 20 K), the system energy density is about an order of magnitude lower that the liquid fuels we presently use. Note that, in turn, these hydrogen storage options are one order of magnitude better than lithium–ion batteries in terms of energy density. For fleets of, for example, taxis or buses, refueled daily and, at a central place, so-called captive fleets, hydrogen might be doable but it is unsure whether this is feasible for passenger cars. Next to the limitations in driving range, the low density also implies that the storage system cost will inherently be (much) higher than what we take for granted with the liquid fuels we use today. Given the high demand for cheap transportation we face today (resulting in the projected growth figures stated above), we need to make sure we convert to a truly scalable solution so cost is a major issue.

V. SO, AGAIN: WHICH ENERGY CARRIER?

We have now determined the three main criteria that should be met by any energy carrier to be used in transportation, before it can be evaluated against other criteria.

1) It should be sustainable, i.e., rely on an infinite energy supply and make use of a closed cycle of resources, but that in itself is not enough, because of 2).
2) It should be scalable, i.e., it should use abundantly available and thus cheap resources.
3) It should be compact, i.e., offer high energy and power density

We believe these criteria are met by renewable, liquid fuels. These can be synthesized using renewable electricity. Liquid fuels are a very efficient way of storing energy and can thus be handled, distributed, and stored in a practical and affordable way.

The question now is: which liquid fuel? We believe simple molecules are to be preferred, as their production is more efficient, requiring less processing steps, and their conversion (i.e., end use) can be controlled more easily (there are less tradeoffs between engine efficiency and emissions). These fuel molecules should be formed from abundantly available building blocks to satisfy the scalability criterion. So we are looking for atoms easily found in the atmosphere or the Earth's crust: carbon, hydrogen, oxygen, nitrogen, and such. Interesting fuel molecules that can be built using these atoms are hydrogen gas (H_2), methane (CH_4), ammonia (NH_3), methanol (CH_3OH), dimethylether (CH_3OCH_3), etc. Wallington *et al.* [5] have worked out this exercise, starting from the periodic table of elements, to select the most interesting fuels. Based on requirements concerning fuel stability, energy density, ease of handling the fuel and its oxidation products (exhaust), sustainability, and scalability, they conclude that liquid hydrocarbons as well as oxygenates are the most interesting options.

Ahlgren [6] concurs that a sustainable society needs renewable, liquid fuels. He advances two fuels, one based on nitrogen, a "nitrofuel," with ammonia serving as example and one based on carbon, a "carbofuel," with methanol as illustration. The nitrogen-based fuel is proposed because of the relative abundance of nitrogen in the atmosphere and the fact it is carbon free. This latter argument is somewhat surprising, as we are now talking about synthesizing fuels from abundantly available building blocks, which are liberated again when the fuels are used. Thus, a closed carbon cycle can be formed and the fact that the fuel contains carbon is no longer an issue. As Wallington *et al.* pointed out [5], it is no surprise that we are now primarily relying on hydrocarbons to fuel our society; this can be concluded from first (chemical) principles: these compounds offer the best features desired from a fuel. Ammonia may offer an acceptable energy density and thus appears to be an attractive energy carrier, but that does not make it a good fuel. In fact, when one studies works reporting the use of ammonia as a fuel, it quickly becomes clear that it is a difficult compound to burn over a wide range of loads such as needed in transport applications. Various tricks are needed, mostly by adding in more reactive fuels, to get it to burn reliably.

Ahlgren advocated a "dual fuel strategy" as he claimed not one fuel exists that covers all the bases.[4] Thus, a second fuel, carbon containing, was proposed because of ammonia's toxicity, implying it cannot be expected to serve as a fuel that can be handled by nonprofessional users. Methanol served as the example of the "carbofuel." Our belief is that, contrary to Ahlgren's view, a single fuel can cover

[4]In fact, Ahlgren denotes a double meaning to the dual fuel strategy, with the second meaning referring to fossil and renewable fuels both being used during the evolution toward a sustainable society.

most applications and that methanol is a compelling candidate.

Methanol can be produced from a variety of sources, in fact being almost as versatile as hydrogen from a production point of view. Not only is it liquid, allowing cheap tanks and cheap distribution, but also it is miscible with gasoline as well as ethanol, the most widely used renewable fuel today. These two facts enable an evolution of the current, fossil-derived fuel to renewable fuel. Possible pathways of introducing methanol (or other sustainable organic fuels) into the transportation fuel pool are presented by Pearson *et al.* [7]. Methanol can also serve as a building block for making more complex hydrocarbons which has led Olah *et al.* to coin "the methanol economy" as a term reflecting the use of methanol as a transportation fuel, energy storage medium as well as raw material for producing synthetic hydrocarbons [8]. Finally, the Massachusetts Institute of Technology (MIT) has proposed methanol engine concepts that promise peak efficiencies of 55%–60%, rivaling fuel cell efficiencies [9].

VI. SO WHERE IS THE METHANOL HYPE?

At this point, one may wonder why methanol seems to be absent from the alternatives enlisted in governmental strategic plans, well-to-wheel reports, etc. In fact, we also struggle to find the precise causes for this. The fact that there is such a multitude of options must be one factor; it is a hard enough task as it is to explain the myriad of possibilities and an even bigger challenge to get the pros and cons of each across, especially to parties looking for a black and white picture. Introducing "yet another" alternative, especially after all "hypes" mentioned in the introduction (and, perhaps more importantly, the falls from grace after some of these hypes, with biofuels being a prime example) is a hard sell. Added to this, the one letter difference between methanol and ethanol does not help either. Perhaps we need to come up with a new name[5] (think of rapeseed oil getting named canola oil to avoid negative connotations).

Methanol's perceived toxicity and safety issues are sometimes used to quickly get it off the table, although there is substantial evidence refuting this myth [8], and this ignores the fact that California had about 15 000 methanol vehicles on the road in the 1980s and 1990s, without any issues. Groundwater contamination in case of a methanol spill is another misconception, confusing methanol with MTBE (methyl tert-butyl ether, an octane-boosting gasoline additive, produced from methanol).

Recently, interest in methanol does seem to be increasing, albeit in perhaps unexpected places. China is currently the largest user of methanol as a road transportation fuel, with methanol accounting for 7%–8% of the transportation fuel pool. Methanol is used as a blending component of gasoline as well as for 100% methanol-fueled vehicles. China's interest arises primarily from the wish to provide a domestic alternative to imported oil, with methanol being mostly produced from coal.

In Europe, methanol is being seriously considered as a viable alternative fuel for shipping. In recent years, much attention has been devoted to the use of liquefied natural gas (LNG) in shipping, as a more cost-effective solution to meeting upcoming emission legislation compared to continuing the use of marine fuel oils which will need complex (and thus costly) solutions to bring down emissions. However, lately, awareness has grown that the distribution and storage of LNG (at −162° C or −260° F), at terminals and onboard ships, is far from straightforward and that it would be more convenient to have the natural gas liquid at room temperature, i.e., convert it to methanol. The Scandinavian Efficient Shipping with Low Emissions (EFFSHIP) project investigated a number of alternative fuels and advanced methanol as the most promising one. Within the Alcohol (Spirits) and Ethers as Marine Fuel (SPIRETH) project, a spin-off from EFFSHIP, a main engine is run on methanol in a laboratory setting, and an auxiliary diesel engine on a Swedish RoPax vessel is fueled with a blend of primarily di-methyl ether (DME), with some residual methanol from the onboard fuel conversion process (with DME being a fuel better suited to direct use in diesel engines and being produced onboard from stored methanol).

VII. THE CAR OF THE FUTURE

So, the car of the future seems to be one that already was running around in the 1980s. Only, in the future, it will get its methanol synthesized from renewable hydrogen and carbon dioxide captured from the atmosphere or geothermal sources. The "classical" internal combustion engine proves to be a sustainable technology, on the condition of converting from the "classical," fossil fuels. Both the ICE and methanol are scalable to the enormous numbers of ICEs needed and quantities of fuel required. Scalability should actually be inherent to sustainability, but, as this does not seem to be the norm, we have stressed its importance separately.

Methanol has been shown to be an excellent ICE fuel that takes advantage from the latest engine technologies to enable high part and peak load efficiencies. Furthermore, methanol's properties offer the potential to further increase the vehicle's efficiency through new concepts on exhaust heat recovery [9]. Furthermore, being an oxygenate, its emissions are very clean. As with any fuel, it presents safety concerns, but these are all mitigated using standard measures [8]. Methanol's main challenge is perhaps its relative obscurity, versus lots of "established" alternative energy carriers. ■

[5] Interestingly, Carbon Recycling International of Iceland is now operating an industrial scale plant, producing methanol from carbon dioxide and energy, both originating from a geothermal power plant, powered by a volcano-powered hot spring. They have branded their synthetic methanol "Vulcanol."

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