THE TRANSITION

Why we need Battery Swapping for the future energy and transport systems

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Battery swapping decouples battery charging from vehicle use. It offers:

- Solution to the problem of decarbonization of heavy long-range transport
- Vehicle use and refueling as simple as today
- Lowest costs for transport:
  » Beats Plug-in and is cheaper than diesel and gasoline
  » Hydrogen powered road transport would result in an annual overcost of the order of 3% of GNP

Grid-connected batteries in swapping stations

- Turn mobility demand into a flexible load, with the capacity to absorb all renewable generation peaks: incorporation of 90% solar and wind generation in the electric system is not a problem
- Provide fast-response firm back-up power to the grid
- Together with longer-term hydro-storage (in the concrete case of Portugal, our model system; this may be different in other countries), stability of the electric system is achieved, with no need for further storage nor high-capacity powerlines for import/export. Investment plans in international connections and in additional storage systems should be reviewed
- Demand of electric energy for road transport is lowest. The hydrogen option would require at least twice as much

These benefits that battery swapping offers come almost for free to the electric system: they are mostly paid for by transport. Electric energy has the lowest costs for the general consumer.

Low-cost electric energy from a stable electric system will encourage faster decarbonization of many other human activities, from buildings to industry.

The battery swapping model of road transport may provide the cheapest, fastest, most socially acceptable, and environmentally benign, path to the simultaneous decarbonization of both road transport and the power system.
Decarbonization of road transport will have a large impact on the electric system: we consume much more energy in the form of diesel or gasoline than as electric energy. When simulating the impact of electric mobility in a decarbonized electric system, we were disappointed by the poor performance of such promising technologies as V2G (vehicle-to-grid) within any realistic assumptions.

This is the reason we decided to study the battery swapping alternative, which decouples battery charging from vehicle use; and the deeper we delved into the study, the more we were struck by how so many problems of the combined road transport and power system were solved by this model for road transport. Battery swapping outperformed so outstandingly all other models that we were surprised to find that our study of the consequences of the BSwap model in a national electric system was the very first one to be published.

In this essay we define the BSwap model, compare it with alternatives, and explore its consequences, confessedly within rough estimates in a simplified world. We hope other researchers and decision makers will deepen and extend this study, and include the BSwap model as an alternative for the future transport and power systems.

António M. Vallera graduated in Electrotechnical Engineering at IST, University of Lisbon, and obtained his PhD in the University of Cambridge (Cavendish Laboratory). He became a professor at the Faculty of Sciences of the University of Lisbon, and retired as vice-rector, but remained active in research.

His long interest in energy focused first on solar technology, but in recent years his main interest is the transition to decarbonized energy and transport systems.
THE TRANSITION

WHY WE NEED BATTERY SWAPPING
FOR THE FUTURE ENERGY AND TRANSPORT SYSTEMS

ANTÓNIO M. VALLERA

Faculdade de Ciências da Universidade de Lisboa
To my family, who put up with my lifelong obsessions, and are the reason I enjoy looking into the future, even if I was infrequently present.

To my colleagues, friends, and students, without whom I might not have embarked upon these thought experiments.
ACKNOWLEDGEMENTS

This essay was written in the sequence of much work and discussions with Miguel Centeno Brito and Pedro Nunes, co-authors of an article published in the scientific journal Energy Policy in 2021 (see reference in Footnote 1). After several seminars, discussions with experts in relevant fields, and ever more discussions with Miguel, it was he who suggested that the fast way to coherently expose my ideas would have to be in book form. I took the challenge, and this is the result.

The text was reviewed by several colleagues and friends, among whom Fernando Caldeira Saraiva, José Medeiros Pinto, Miguel Centeno Brito, António Sá da Costa, Killian Lobato, António Ermida Mano, João Almeida Serra and Jorge Maia Alves, a few of whom read it thoroughly and wouldn’t give up until all was clear to them, but I wish to extend my acknowledgements to all who gave their very welcome contributions.

I wish to thank the University of Lisbon, and namely its Faculty of Sciences and Instituto Dom Luiz research centre, for the conditions they offered to the continuation of my research work after my retirement as a professor.

This work was partially financed by Fundação para a Ciência e a Tecnologia, I.P./MCTES with national funds (PIDDAC) –UIDB/50019/2020.
We are accelerating into a transition towards the future energy systems, and the most immediately and profoundly affected sectors are the electric system and road transport. Countries all over the world are preparing plans for deep decarbonization of these two sectors, because it is needed, and because it is technically feasible.

There are several ways of achieving this; the main aim of this work is precisely to compare the outcomes of different models for the decarbonization of road transport.

Three alternative models for decarbonized road transport are considered, and compared to the incumbent model of vehicles powered by fossil fuels:

1. ICE model: vehicles are powered by internal combustion engines that burn diesel oil or gasoline.
2. H2 model: vehicles are powered by fuel cells running on green hydrogen.
3. Plug-in model: vehicles are battery electric and charged by plugging a cable in the socket of public or home chargers.
4. BSwap model: vehicles are battery electric but swap their low charge batteries for charged ones in battery swap (BSwap) stations.

The choice of one of the models has far-reaching consequences, well beyond the simple choice of a vehicle: it will affect the whole economy, the climate change, the way we live. And once a model is politically chosen and investments are made, it becomes increasingly difficult, and expensive, to switch to another, better, solution. Our common road splits ahead into different directions, and our choice now will profoundly affect our future. We are approaching a moment of difficult return, and decisions must be taken with as much knowledge of their consequences as possible. Thus, the urgency.

You will find, as I did when I plunged deeper into this study, that the dismissed, overlooked, Battery Swap (BSwap) model stands out immensely over the others. The basic reasons for this are the following:

a) The main problem of most future, decarbonized, electric systems is imbalance (namely due to the future dominance of generation technologies such as solar PV and wind, which cannot follow demand): the cost of balancing the system may become even higher than energy generation itself.

b) Road transport will weigh heavily on the electric system (presently, the energy consumption by all vehicles for road transport, mostly in the form of liquid fuels, is about 135% that of electric energy consumption in most countries):
i) If road transport were decarbonized now via battery electric vehicles, we would need to increase electric generation by 54% (assuming an average gain in efficiency of 2.5 when substituting combustion motors by electric traction); if the choice were hydrogen, then a 130% increase might not be enough; with synthetic fuels, perhaps 200% would be needed.

ii) The mechanical power of vehicle motors is very high, in the order of 100 times the average power supplied by the electric system. If we decarbonized now, the nominal power of batteries in electric vehicles would be about the same.

c) The consequences are that

i) If just 10% of these batteries were grid connected for charging (10% corresponds to an average grid-connection time per battery of about one day, in a BSwap model for road transport; these are sufficient to provide all needs for road transport), their nominal power capacity would be many times greater than the average power supplied by the grid to satisfy all electric energy consumption.

ii) If these batteries are grid-connected for 24 hours, then charging may occur at the most convenient times for the electric system, which results in a large grid balancing effect.

iii) Electric energy supply for road transport becomes a fully flexible load to the electric system, corresponding to a relevant fraction (20 - 30%) of the total electric energy consumption, and with such a power capacity that it can easily absorb all excess generation peaks. Also, these grid-connected batteries may provide firm power to the grid, to support it when needed.

This is the basis of the Battery Swap model for mobility, which

- Is superior to the other alternatives from the point of view of electric system balance, with the advantage that the benefits it offers are mostly paid for by transport. Two important consequences: (1) massive renewable energy penetration into the electric power system is not a problem, allowing its fast decarbonization, and (2) electric energy will be inexpensive.
- Allows vehicle use as simple as today, with no autonomy or time to refuel problems; and solves the problem of decarbonization of heavy long-range transport. Also, we demonstrate that Battery Swapping is the least expensive of the road transport models, proving even less costly than diesel and gasoline powered transport. This should allow the transition to occur at an accelerated pace.
- Has the potential to be the fastest, cheapest, and most benign path to decarbonization, primarily via the full decarbonization of the power and road transport sectors, then indirectly, via its contribution to a stable power system supplying decarbonized electric energy at a low cost, lower than that of decarbonized gas: many other activities (e.g. in buildings and industries) will shift from gas to all-electric energy supply, and much of the immense source of pollution deriving from burning fuels will cease.

And yet almost no one is considering BSwap as more than a local issue, say of a network of buses in a town, or a corporate strategy of an automotive company. I was really surprised to find out that our study of the outcomes of a BSwap model applied to a national system was the very first one to be

\[1\text{Why we need battery swapping technology, A.M. Vallera, P.M. Nunes, and M.C. Brito, Energy Policy 157, October 2021, 112481, https://doi.org/10.1016/j.enpol.2021.112481}\]
published. Most automotive companies are taking plug-in charging as the obvious solution for private cars or light duty vehicles, while heavy truck companies are deciding between plug-in or jumping onto the hydrogen bandwagon, a solution that is being sold as the rise of a new era for transport and energy systems all over the world. Look beyond, and deeper, is my message.

Lisbon, the 5th of May 2022
António M. Varella
A NOTE ON METHODOLOGY AND TEXT:

This text is meant to reveal to the interested, informed, public, the consequences of each of the possible options we’ll be called to decide upon for road transport in the near future. The aim is to contribute to a better understanding of the issues, and of what is at stake. The work behind it is largely the result of the construction of models used for the calculations aimed at revealing the outcomes. We try to explain how the results were obtained, and I hope the general reader feels reassured enough about their credibility. However, since full description of the methodology and assumptions is inappropriate in the context of this essay, the reader who wants to know more of the fundamentals of the work is advised to obtain further information from the scientific papers already published or to be published on this subject.

We tried to balance readability and rigour, using frequently common expressions rather than more technically charged jargon, and avoiding underlying complexities that would divert the reader into meanders that would be laborious and unnecessary to navigate, and distracting from the major issues we want to address.

A NOTE ON REFERENCES:

This work used information from hundreds of publications, from scientific journal articles to white papers, reports, news, and roadmaps, and also from conferences and private conversations. I decided not to cite them for three reasons: on one hand, one of the main aims of this work is to provoke others into performing their own calculations, using their own data; on the other, the essential data are readily available for the interested reader, and technology and policy are changing so fast that I encourage the reader to search for state-of-the-art science and technology, and up-to-date roadmaps and policies, while sieving the information always with a scientifically critical eye, particularly that produced by direct stakeholders; finally, citations would frequently require comments and justifications, which would result in a heavier text to read. The result is a less ponderous, lighter text, with many footnotes to justify, illustrate, or extend information in the main text, but very few cited references.
Daniel pulled his 40-ton truck off the highway into one of the old regular service stations. It wasn’t time for his compulsory rest yet, so he stayed aboard while the low-charged batteries were swapped for charged ones. The operation took about three minutes, payment included, with no human intervention, and he steered back onto the highway, looking forward to lunch with friends further down the road.

How things had changed so dramatically in only a few years, he thought. He was happy with his decision to replace the old diesel truck for this electric truck six years ago. In fact, once he had weighed the options, it was a no brainer: it was cheaper than a new diesel truck, and the annual expense with battery swapping was less than he would pay for diesel. He had also considered a hydrogen powered alternative, but all the numbers were so much worse: the truck was way more expensive, and the annual cost of fuel, repair, and maintenance so much higher! No wonder there were so few of them. The same change was happening with light vehicles: only a few service stations kept one or two old pumps, almost all of them had been replaced by battery swapping spots. Also, the old public charging pillars were slowly starting to disappear. They were expensive to install and maintain, and the charging fee was high. And as drivers saw how battery swapping was so much more convenient, they started buying the new cars, not the old plug-in ones. In fact, the use of electric vehicles had become as convenient as in the old times of diesel motors and pump stations. No range anxiety, no search for a vacant fast-charge spot, no cables and urban streets littered with charging pillars.

He felt a sense of pride in helping change the world. Both the electric system and road transport were on track for almost no climate change emissions; in fact, both sectors were helping each other do it. How such a simple technology, battery swapping, made this possible so rapidly, he wondered. A Columbus egg idea with such a disruptive impact. Also in industry: he had read that now the electric system was balanced, and electricity cheaper than gas, many industries were replacing fuels with electric energy. Even industries that need high temperature process heat, such as glass, ceramics, even cement, were joining the electrification revolution. And because they were not burning fuels anymore, there was no need of huge fluxes of fresh air for oxygen, so some of the new factories were already using the process gas in a closed loop: heated gas injected for process, then scrub off dust and all deleterious gases for clean disposal, and back to re-injection. No more spewing chimneys. Hydrogen was also being obtained from electricity, wherever it was needed for chemical reasons: in fertilizers, plastics, food, in the steel industry, and in fuels for ships and planes. The consequence: emissions from the industry sector were also declining fast.

And this was happening all over the world: even in countries that were previously starved for
energy and had been massively installing dirty coal power stations, the huge increase in electricity consumption for transport and all human activities was now being satisfied by clean, renewable energy. Put it this way: if I were crossing Asia with my truck, with every refuel of fresh charged batteries, I would be filling it up with clean, locally produced, energy, rather than with energy from an oil well or a spewing coal plant hundreds of kilometres away. And people in remote places now had better access to stable, clean, and cheap electricity.
THE TRANSITION • Why we need battery swapping for the future energy and transport systems

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LIST OF ACRONYMS

**BEV**  Battery electric vehicle
**BSwap** A model for road transport that uses battery swapping (the exchange of low-charge batteries for charged ones) for refuelling electric vehicles. Several variants of the generic model are referred in the text, e.g. BSwap Flex 24h, BSwap Flex 48h, BSwap+, BSwap.
**BSS**  Battery Swapping Station, where EVs may swap their low-charge batteries for charged ones. Most BSSs might be an evolution of the old fuel stations.
**B2G**  Battery-to-Grid, a technology that allows bidirectionality of the connection of a battery to the grid, allowing grid support, for instance in case of (but not limited to) an unexpected generation outage or of power deficit in the grid.
**EV**  Electric vehicle.
**HEV**  Heavy Electric Vehicle
**LEV**  Light Electric Vehicle.
**GNP**  Gross National Product
**H2** A model for road transport relying on hydrogen fuel-cell powered vehicles.
**ICE** A model for road transport in which vehicles are powered by Internal Combustion Engines that burn liquid or gaseous fuels.
**HHV** (Higher Heat Value) refers to the total energy content of a fuel.
**LHV** (Lower Heat Value) equals HHV minus the latent heat of the water vapour generated during its combustion (against its condensate form, liquid water).
**Imb(t)** The imbalance function (defined as demand minus generation) of an electric system as a function of time.
**Plug-in** A model for road transport based on battery electric vehicles that charge their on-board batteries by plugging a cable into an electric power socket.
**V2G** Vehicle-to-Grid, a technology that allows bidirectionality of the connection of a Plug-in vehicle to the grid, allowing grid support in case of power deficit in the grid.
I • INTRODUCTION

Climate is changing, and greenhouse gas emissions by human activity must be reduced. Road transport and electric energy generation are responsible for almost a half of all emissions\(^2\) and their deep decarbonization is now seen as technically feasible. It is therefore only natural that most plans being put forward all over the world focus especially on these two sectors, and they are the focus of this essay too.

Road transport

We assume that road transport decarbonization will be made via traction by electric motors\(^3\); the discussion is then on how electric energy should reach the motor. The aim of this essay is precisely to compare three\(^ 4\) different ways of doing it, and test them against the incumbent model of vehicles powered by internal combustion engines (ICE) that burn fossil fuels:

1. **ICE model**: road transport relies on internal combustion engines running on diesel oil or gasoline.
2. **H\(_2\) model**: vehicles are powered by fuel cells running on green hydrogen.
3. **Plug-in model**: vehicles are battery electric and charged by plugging a cable into the socket of public, company, or home chargers.
4. **BSwap model**: vehicles are battery electric but swap their low charge batteries for charged ones in battery swapping stations (BSSs).

The reader may think that one model may have some benefits over the other, but that’s it, the market will decide on the winner, end of the story. However, it is not so simple: each of the models has very far-reaching consequences, well beyond the simple choice of a vehicle. The choice of one of the models will affect the whole economy, the climate change, and the way we live, as we shall try to demonstrate.

Most numerical examples below are from Portugal, the region we chose as the inspiration to

---

\(^1\)Road transport accounts for about ¾ of all transport emissions and is more amenable to fast decarbonization than air and sea transport, which account for most of the remaining ¼. Together, transport and electric energy generation account for 54\% of global emissions; industry, buildings and agriculture come next, with smaller fractions.

\(^2\)The alternative, championed by some, namely for heavy vehicles, would be to continue using internal combustion engines, burning fuels that are nearly carbon neutral, namely biofuels (biogas, alcohols, biodiesel) and e-fuels (synthesized using electricity, e.g. e-diesel). While such fuels might be a solution for air or sea transport, we think they will never compete with the far more efficient and cheaper solutions that use electric traction. (This isn’t consensual yet, as demonstrated by the present European controversy on how heavy goods vehicles should be powered in the future.)

\(^3\)We have also studied a fourth model, in which long-range heavy vehicles are powered by overhanging catenaries. However, the outcomes are not sufficiently different from the Plug-in case to justify a separate model entry in this study.
construct a simplified concrete system to which our road transport models were applied; however, the methodology may be applied to any country or region. We hope our work will stimulate many others to study their own transport and power systems, and to quantify how the outcomes of the battery swap (BSwap) model fare versus other models. We are convinced that BSwap will prove superior to other models in most countries of any continent.

The electric system

Electric generation is still dominated by fossil fuels worldwide, especially coal and natural gas. Decarbonization may result from progressive substitution of present fossil fuel power stations by generation

1. from renewable energy sources,
2. from nuclear reactors, or
3. from fossil fuel power stations which capture and re-use or geologically store the carbon dioxide resulting from fossil fuel burning.

On a cost basis (including economic, environmental, and social impacts) renewable energy is arguably the best solution in most regions, but there is no recipe for all: each region is actively discussing which mix might be the best, depending on local resources. Let us briefly discuss some of the relevant components of this mix:

Hydropower is an excellent technology: where it is available, it has the precious advantage of easily adapting generation to demand (it is dispatchable, in technical jargon) and so may have a very relevant role in balancing the electric system. However, the hydric resource is very limited and much of it already exploited: on a global scale, it might satisfy only a small fraction of future needs. In Portugal, hydropower is mostly exploited already, and by 2050 might account for only 10% of total generation. We cannot count on hydropower to displace fossil fuel generation.

Generation from burning biomass and residues has in common with hydropower being dispatchable and resource limited: sustainable exploration might satisfy only a small fraction of future needs, about 7% in the case of Portugal.

On the contrary, in most regions, solar and wind generation are not resource limited. As an example, Portugal’s total present electric energy needs might be supplied by solar photovoltaic

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1 This mix may include heavy reliance on energy import or export. In some regions, for instance, it may be better to import a large fraction of the electric power than try to generate it locally.

2 There are, of course, limitations to this hydropower generation flexibility. Large reservoirs, because of their large capacity, are the most flexible, and can be made even more so if water pumping from a lower reservoir is added. However, even the so-called run-of-river hydropower generators, or even the very small hydro power stations, have some capacity to adapt their output to demand. They cannot, of course, offer longer term response, e.g. they cannot compensate seasonal variations: their small reservoirs cannot store the natural flow of the rivers for longer than, say, one day (depending on flow and storage capacity for the allowed water level change). We have modelled and taken into account the contribution of run-of-river and small hydro stations, in our calculations of the response of the national hydropower system in Chapter III.

3 Several proposals for presently unused capacity in a few Portuguese river basins have been stopped by environmental considerations. A few others are planned, and others may be decided in the future.

4 Hydropower has a high annual variability. The cited percentage is just an expected average value.

5 The possibility of residues/biomass thermal power stations contributing to electric system balance is conspicuously absent presently in Portugal, a perverse consequence of inadequate regulation. (Presently, these power stations generate at a constant rate virtually all year round.)

6 We shall adopt the number cited in the present Portuguese roadmap, although we suspect that in practice it might be lower.
modules occupying an area of 0.3% of its territory, about the same as the artificial lake of Alqueva, on the Guadiana River.

Electric energy generated from wind and sun is cheap, with reference costs of

\[0.03 \text{ to } 0.07\, \text{€/kWh}\]

in Portugal, with present technology (to be compared with more than 0.11€/kWh for nuclear\(^{11}\), and about 0.20€/kWh we pay at home in Europe). Where they are abundant and cheap, solar and wind are obvious choices to support the future substitution of fossil fuel generation and the future increase of electric energy demand due to progressive electrification of our society\(^{12}\).

There is a snag, though: solar and wind generation are variable, non-dispatchable resources, cannot adapt to demand needs. If we install enough wind turbines and solar panels to satisfy most of our growing energy needs, and to substitute the old fossil fuel power stations, most of the time demand will be either unsatisfied (because the sun is not shining and the wind not blowing enough) or the system will have a lot of excess power (if the sun shines and the wind blows). The central problem of the future electric system is no longer the cost (economic, environmental) of generation, it is electric system imbalance.

Or, in other words, the cost of balancing the system, ensuring quality of service, and security of supply. Our study of the electric system in Chapter 3 quantifies this central problem.

**The impact of electric mobility on the electric system**

Apart from the road transport sector itself, the most direct impact of decarbonizing road transport will be on the electric system, since all the decarbonized mobility models considered here use electric energy as their primary source. And it will be a very relevant impact, because we presently consume more energy on transport (mainly in the form of diesel oil or gasoline) than we consume as electric energy. Energy spent on road transport alone is of the order of 135% of electric energy consumption in most countries\(^{13}\), as shown in Table 1.1.

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\(^{11}\) See, for instance, the case of the new nuclear power station at Hinckley Point, UK. Frequently cited low energy costs for nuclear energy refer to old reactors, built several decades ago, which have the initial investment cost fully amortized. Here we are interested in the energy transition and therefore must consider new nuclear energy to substitute fossil fuels, and new nuclear is not cheap, as all recent examples demonstrate.

\(^{12}\) Despite all efficiency measures we may apply, electric energy generation is bound to increase, if we are to attain or maintain levels of civilized comfort in our society. Energy hunger is not a solution.

\(^{13}\) The global ratio is 130%, brought to a lower value than most countries particularly by China, the odd one here, due to its recent historic evolution: it has the largest electric system in the world, having passed the USA in 2009, but the per capita number of vehicles was still 1/2000 in year 2000. This ratio has been growing extremely fast since then (e.g. by 21% from 2019 to 2020), reaching 1/4 in 2021. Precisely because China still has an immature road transport system, and its growth happens just at a transition time, it will be very interesting to accompany its decisions on mobility and the resulting outcomes.
THE TRANSITION

Why we need battery swapping for the future energy and transport systems

<table>
<thead>
<tr>
<th>Country</th>
<th>Energy spent on road transport (TWh)</th>
<th>Electric energy consumption (TWh)</th>
<th>(Energy consumed in road transport) (Electric energy consumption) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>32 230</td>
<td>24 881</td>
<td>130 %</td>
</tr>
<tr>
<td>Portugal</td>
<td>65</td>
<td>48</td>
<td>137 %</td>
</tr>
<tr>
<td>EU</td>
<td>3 556</td>
<td>2 647</td>
<td>134 %</td>
</tr>
<tr>
<td>USA</td>
<td>5 981</td>
<td>3 961</td>
<td>136 %</td>
</tr>
<tr>
<td>China</td>
<td>4 467</td>
<td>6 753</td>
<td>66 %</td>
</tr>
</tbody>
</table>

**TABLE 1.1** Ratio of energy consumed in road transport and in the form of electric energy in 2019. (See Footnote 13 on the Chinese discrepancy.)

This means that electric energy generation would have to more than duplicate, to 235% of present electricity generation, just to satisfy road transport demand, if there were no other changes in transport, be it in (i) how people and goods move about, or in (ii) efficiency changes in the transition from internal combustion engines to electric traction. Since the electric system must simultaneously wean itself from fossil fuel generation, and we must do this fast (we look at 2050 as the year when deep decarbonization of our economies should have been mostly realized) because of climate change, this all adds up to a prodigious transition, a change in our societies so profound and so fast that we need to mobilize our focus and investments.

A striking example of the possible impact of transport decarbonization on the electric system is illustrated in Figure 1.1, where the estimated electric energy needed just to power European trucks by 2050 is compared with total renewable electric energy generation in the EU 2017. The energy needs were estimated for three different models to power heavy road transport, using

- Battery electric trucks,
- Hydrogen fuel cell trucks, and
- Synthetic fuels.

Notice that about a half of all present renewable electric generation in Europe would be needed just to power the battery electric trucks¹⁴, but if hydrogen is chosen, then all that generation is not enough, and, with synthetic fuels, even double that generation would be insufficient. This is a sobering call to reality, illustrating how relevant energy conversion efficiency is, and pointing out obvious targets for technical development that must be met.

¹⁴ Or batteries plus overhanging power catenaries, the total consumption would be about the same.
The transition

This transition is not a pure technical nor economical issue, because it will affect profoundly our lives. This is why decarbonization models for the two coupled systems, transport and electricity, deserve careful consideration: each model will affect us differently, be it in how fast the transition may occur, in the cost we shall pay for it, in the way we move about, or how we restructure our cities and industries.

In the next chapters, we detail the models and the results of the calculations carried out, and how the different models lead to different outcomes; here we shall just touch upon a few of the issues of each model,

- emissions and speed of transition,
- energy,
- electric system balance, and
- cost.

Sources: Transport & Environment, How to decarbonize European transport by 2050 (2018), and European Commission, EU Energy in Figures (2019).
Emissions

All three electric traction transport models (Plug-in, H2, and BSwap) are compatible with deep decarbonization in the long run, if the electric system is simultaneously decarbonized. Since most of the emissions from transport are due to fuel burning, in a first approximation\textsuperscript{16} we shall not distinguish the three electric vehicle (EV) models because of emissions.

The effect will be dramatic, with almost 50% reduction of global emissions from road transport and electric generation alone. However, this isn’t all: decarbonization of these sectors may impact positively all other sectors. For instance, industry and buildings would certainly diminish their emissions too, if we achieve decarbonized electric energy at a low cost. How these different transport models will affect electricity prices is a crucial point, not only economically, but also emissions wise.

How fast may be this transition to lower emissions? This is also an important point, and you may guess that one model may have advantages over another. However, here we shall limit the analysis to a few qualitative and speculative comments, to stimulate work of others on the pace at which the transition may occur.

Energy

Energy demand for transport from the electric system depends on how people and goods move, but also, and more relevant for model comparison, on the efficiency of how we bring energy from the electric system to the on-board electric motors of vehicles.

Since our main interest is distinguishing the models, we assume, for all of them, the same mobility pattern, and the same final energy consumption for transport, which we define as that which is required at the level of the electric traction motors\textsuperscript{17} or the equivalent mechanical energy in the ICE case.

Electric system balance

We stated above that the central problem of the future, decarbonized, electric system will be system imbalance, particularly because of the increase of solar and wind non-dispatchable generation\textsuperscript{18}. The problem may be mitigated by a combination of

1. energy storage (\textit{e.g.} by pumping water from a lower into a higher reservoir, and use it later when needed)
2. demand flexibility (\textit{e.g.} encouraging/discouraging use of energy in hours of plenty/scarcity \textit{e.g.} via different energy tariffs)
3. excess generation capacity\textsuperscript{19}(necessary to mitigate shortages in times of scarcity),

\textsuperscript{16}If we go deeper in the detail of each alternative model, second order differences in emissions will appear, as well as other very relevant issues such as those concerning future materials needs, but we shall not discuss these here.

\textsuperscript{17}Which is not much different from that which would be measured at the wheels, since electric motors are very efficient, and the mechanical torque transmission from motors to wheels is also very efficient (more so than in ICE powered vehicles). One advantage of this option is that efficiency defined this way coincides with the notion of round-trip efficiency, the electric final energy that is used for traction per unit electric energy taken from the electric system. Another advantage is that this definition focuses on the model distinguishing feature, not in other details.

\textsuperscript{18}We might add nuclear energy as well, since nuclear reactors work well at constant output, with no adaptation to changes in demand. In practice, it might be classified also as a non-dispatchable source of energy. (In principle, it is possible to vary the output to some extent, but it would be more expensive, and most frequently it is not done.)

\textsuperscript{19}Chosen as an adequate balance between demand needs and renewable power generation capacity; some excess in generation capacity may help to deal with uncertainty and scarcity periods of renewable resource availability.
introduction

Why we need battery swapping for the future energy and transport systems

4. curtailment \(^{20}\) (the intentional limitation of generation from, say, a wind or solar generator, when generation power capacity exceeds the capacity of the electric system to absorb it), and

5. import/export of electricity across the region border as needed.

It can be done, but in future systems, with a large proportion of non-dispatchable generation, system balance achieved by such procedures may imply a high additional cost of energy: it will be vital to choose the best combination of balancing assets.

How will future electric mobility affect this problem? Will this transition in mobility exacerbate it, because the electric system must expand its generation capacity to satisfy the extra demand by mobility, and this expansion will probably be achieved by still more non-dispatchable sources, such as solar and wind? Or will it somehow help mitigate it?

This is a very crucial point to analyse when discussing the electric system, because there may be a large difference in global cost to the economy if the different models affect differently system balance.

Cost

If we are to make an informed decision among alternatives, these must be compared in a level playing field. To achieve this in a meaningful, yet understandable, way, our choice was to use, for both the electric system and road transport, models which are highly simplified but retain the most relevant, choice determining, matters.

Outline

This essay is organized into the following chapters:

Chapter II - The transition: road transport, aims at finding the significant differences in the outcomes from each of the road transport models. First, we describe the models, with special detail for battery swapping (BSwap), because it might be unfamiliar to the reader, and overlooked by decision makers, contrary to the others. Then we present and discuss the results for each model, from the points of view of different stakeholders.

In Chapter III - The transition: electric power sector, we focus on the impact of the road transport models on the electric system.

In Chapter IV - The transition: combined Road Transport and Power sectors, we discuss the results for the two coupled sectors.

In Chapter V - How universal are these conclusions?, we look at the variety of present electric energy matrices in countries around the world, and qualitatively discuss the possible impacts of the road mobility models. We propose a model for the expansion of electric energy consumption by road transport through locally generated renewable energy.

In Chapter VI - The transition: substitution of fossil fuels, we discuss the consequences of the transition for industries and other activities, focusing on how they may be weaned from fossil fuels. We show that the different models for mobility will strongly impact the outcomes for activities well beyond those directly connected to road transport, from heavy industries to buildings.

In Chapter VII - The transition: public policy, we discuss the possible role of public policy in creating the conditions for facilitating and speeding up the best transition models.

Finally, in Chapter VIII - The choice, we wrap-up the main conclusion of our study.

\(^{20}\) Technical jargon for throwing away energy, even before it is produced.
We present further information, such as technical data or general considerations, in the form of Annexes, so that the main flow of the essay is smoother.

The alternative visions that we share here are far from worked out in detail. In fact, one of our motivations is precisely to stimulate colleagues all over the world to consider and apply these and other alternatives to their regional systems, and delve deeper and in more detail into technical, economic, environmental, and social consequences for better defined, more realistic, models, and to search for the roadmaps and policy actions that may lead to the best overall outcomes.

We do not attempt to present a realistic proposition, and even less a roadmap. We focus instead on the crucial differences resulting from the four road transport models in snapshot alternative visions of the future, part of them aimed at an intermediate stage of the transition, say the mid 2030’s, and another part aimed at 2050, when we assume most of the transition has been realized.

The reason for this approach is that alternatives are easier to study, and the consequences of the different choices come out crystal clear, unclouded by all the noise that would be inevitable in a real-world simulation. The models used in this approach are intentionally simplified to the bone, using highly purified models for both the electric system and road transport, but retaining the most relevant, choice determining, matters, as stated above.

21 The three electric traction models, plus the incumbent ICE.
II • ROAD TRANSPORT

The main aim of this chapter is to estimate the differences in cost and energy consumption that result from the four models for road transport 22.

As stated before, this is not a roadmap, it is rather a snapshot vision of a future time, because it would be unfair for developing technologies such as H2 to be compared with a mature technology such as ICE, using present efficiencies and costs. Our choice of the time for comparison was therefore set to sometime in the future (mid 2030’s?), when technologies are not yet mature but on the way to it: we use expected achievements for each technology by that time, and assume their share of the market is still expanding (we assume in most cases an expansion of 6%/year, and a technology cost decrease of 1%/year, the reason being to check how able they are to support market growth without subsidies).

Before we present the results, we first clarify some of the aims and assumptions.

Points of view

Conflicting points of view frequently arise when costs are discussed 23. We therefore tried to avoid one-sided visions of the system by checking the consequences of each model from the very microscopic to the macroscopic perspectives. For road transport, we present the points of view of

- the owner of a heavy, long range, 40-ton tractor and trailer
- the owner of a light, mid-class, passenger vehicle
- the infrastructure owner and service provider
- the road transport sector, with reference to a few other stakeholders

22 The values we use here for the model parameters are a personal guess, based on many conflicting sources, and using a skeptical eye on claims of future developments by direct stakeholders. The result is the best we could obtain at this time; it needs continuous updating in the future, incorporating the results of technological progress. An example: one of the critical parameters is the energy consumption tank-to-electric motor, or battery-to-electric motor. For battery electric vehicles, we used present values, because they are already quite efficient, and so we do not expect substantial improvement; on the contrary, for hydrogen, we used for a mid-class passenger vehicle a consumption of 0.8 kg H2/100 km, a 25% increase in efficiency from the best present (which is just reaching 1.0 kg H2/100 km): we incorporated possible improvements in fuel-cell performance.

23 The main model parameters are summarized in Annex 3.

These may be exacerbated e.g. by a distortion of the market by fiscal or other state intervention (stimulation of a given technology or sector is seen by others as expensive and punishing), or to unfair distribution among stakeholders (some might manage to have the bigger piece of the cake).
Cost components

Since our main aim is to distinguish the four road mobility models, we simplify more general problems such as total cost of ownership or global sector cost by taking into our calculations only the components that are relevant for model distinction. On the road transport side, we analyse:

1. Vehicle cost, sub-divided into
   a) Basic vehicle cost: we assume that similar vehicles, be they powered by fuel (ICE), hydrogen (H2), Plug-in batteries or swappable batteries (BSwap), will have a similar cost for all except the power module.
   b) Power module cost: it includes motors, transmission, fuel cells and tank, power electronics and control systems, batteries, everything that has to do with powering the vehicle. This component of vehicle cost is very model dependent: a diesel motor and transmission is more expensive than traction electric motors and power electronics alone, but less expensive if one adds in fuel cells and batteries.

These investment costs were annualized using constant payments at a 6% rate and 8 years amortization period, when calculating the costs from the microscopic point of view of a vehicle owner. When we later consider sector costs, we use a total useful life approach for vehicles, which differs namely in the need to include substitution of important parts of the vehicles, such as batteries and fuel cells. A 6% growth rate of the number of new vehicles was also assumed.

2. Repair and maintenance cost
   Values for ICE vehicles are available, but for EVs (battery or H2) they are not well established. We chose values for EV models which are referred as expectable: repair and maintenance of a battery vehicle should cost about a half that for an ICE vehicle (due to very low maintenance costs for electric versus ICE motors), while we assume, perhaps optimistically, that H2 vehicles might fall halfway.

3. Energy cost
   This is a highly distinguishing component of cost, so it deserves to be analysed in more detail. For ICE, we use two different costs for fuel, one that represents the cost in the EU without special taxes (which we took as 0.65 €/l), the other an average of retail price in the EU, including all special taxes (1.30 €/l). The main reasons for this are the very different perspectives of, say, a truck owner, or of the government looking at sector costs and contributions. Also, this double value reveals the sensitivity of global road transport cost to fuel cost, and is useful when

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24 Frequently used as relevant for the owner of a vehicle fleet.
25 One major component of transport cost, the ease of vehicle use, was not quantified here, even though it is model sensitive. This is especially important in the case of heavy or shared vehicles, for which e.g. the Plug-in model may have higher constraints than BSwap or H2, due to time-to-refuel differences, which translate into higher costs for transport services. This component should of course be quantified into costs in future work, here we only qualitatively mention it.
26 See, for instance, A. König et al., https://doi.org/10.3390/wevj12010021.
27 Scania stated in 2021 that high costs of repair and maintenance of their hydrogen powered trucks were one of the reasons to abandon hydrogen technology and shift to battery technology.
28 Such values are, of course, rather variable. The ones used here were considered a reasonably representative choice for recent years, determined by a relatively stable cost structure in the industry, obviously before the present extraordinary events.
considering inclusion of external costs (environmental, economic, social) in fossil fuels use. For all EVs, the cost of energy as defined here goes back to how much is paid for it to the electric system, which is where the energy of EVs comes from. In other words, it is not the price of hydrogen at the dispenser, nor the price of plug-in charging or battery swapping: it is the cost of the energy taken from the electric system. It is not a trivial problem to estimate this cost; we simplified the problem by assuming a guessed average cost of electric energy for each model, focusing on the model differences rather on absolute values for energy. For both H2 and BSwap, the energy cost was set at the low value of 40 €/MWh, assuming that demand is totally flexible in both models, and energy, if imported from the grid, will be paid at the lowest prices, close to generation costs. In a deeper study, we should also take into account the value of (1) grid services (with respect to which BSwap might fare better than H2), and of (2) dedicated generation, but these are discussed but not quantified below. On the contrary, the Plug-in model has limited possibilities for demand flexibility and for grid services, and so we chose, for the cost of energy, a value somewhere between an average industrial tariff (for public and company chargers) and private home tariff (for home charging), set at 100 €/MWh for heavy vehicles and at 150 €/MWh for light ones. (We do not assume that these guessed values reflect the “true” cost of the electric system to supply energy in these different conditions: they are just average tariffs that we assume, as model parameters, that the transport sector pays for energy. We revisit this issue in Chapter III, when studying the electric system, and in Chapter IV we finally eliminate this issue from the conclusions, when we consider the combined, coupled, transport and power systems.)

How much energy is taken from the electric system depends on the energy efficiency of each model, and this is a very important distinguishing model parameter, as discussed below.

4. Cost of infrastructures necessary to bring energy from the electric system into the EVs

Note that for ICE the infrastructure cost is already incorporated in the price of fuel, and so this additional cost is set at zero for ICE. It only applies to the electric models.

For H2, this is the cost of infrastructures to produce, distribute and dispense hydrogen (includes electrolyser plants, and all the network to store, compress, distribute and dispense hydrogen to the vehicles).

For Plug-in, the cost of installing and maintaining operational chargers, public or private.

For BSwap, the cost of battery swap stations (which includes robots, chargers, grid connection, power electronics and control systems, installation costs, operation and maintenance).

In all these cases, a net growth rate of new infrastructures of 6%/year and a cost decrease of 1%/year was assumed in this chapter. The financial costs were constant payments at 6% interest and 15 years depreciation and substitution.

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29 Examples of difficulties: (1) cost varies with market conditions, (2) and, furthermore, it will be a consequence of the impact of electric mobility on the electric system itself; (3) the electric system supplying the energy may be the grid, or the grid plus dedicated parts of the system (islands not connected to the grid, e.g. solar or wind generation exclusively dedicated to EV mobility or hydrogen generation).

30 Which may be iteratively perfected by analysis of the impacts of mobility on the costs for the electric system.

31 On flexibility, think of fast charging while travelling: no flexibility is possible, you want the energy immediately and fast. As for grid services, the much-discussed vehicle-to-grid (V2G) concept is extremely limited: think who would be prepared to degrade his vehicle's battery and accept less EV availability for a very few euros per month.
Energy efficiency

The final energy demand was set equal for all electric models and defined as the electric energy measured at the cables that feed the traction electric motors. The energy effectively taken from the electric system is of course higher, and a measure of how inefficient the transfer process is.

Consider a Plug-in battery electric vehicle. To estimate its grid-to-motor efficiency, one may define four process steps,

1. electric grid-to-charger output,
2. charger output-to-battery,
3. battery in-to-battery out, and
4. battery out-to-motor,

each with energy conversion with an efficiency below 100%: some energy is lost in the cables, transformers, power electronics, and the battery itself. The overall process starts with electric energy taken from the grid and ends with electric energy fed to the motors. The global efficiency of this grid-to-motor process, which we call a “round-trip efficiency”\(^{32}\), is defined as the ratio of final electric energy (fed to the motors) over the electric energy taken from the system (the primary energy: for electric vehicles the electric system is the primary source) and equals the product of the efficiencies of each step.

Assume, as an example, a Plug-in vehicle with a global round-trip efficiency of 80% (grid-to-motor); this means that the electric energy taken from the grid would be 125% the final energy fed to the motors\(^{33}\).

This relatively high efficiency is mostly due to the excellent performance of current EV batteries, which easily demonstrate efficiencies over 95% for low rates of charge/discharge, coming down to about 85% for very high rates, at peak power charging/discharging. In present practice, most of the round-trip efficiency loss comes from the electronic system that manages power into and out of the batteries, not from the batteries themselves. Depending on how much fast charging/discharging is necessary, average round-trip efficiencies are between 75% and 90%, thus justifying the 80% value used above.

This good efficiency grid-to-motor coupled with the excellent efficiency of electric motors is the reason\(^{34}\) why, when you compare two current, similar class, vehicles, with similar use and distance travelled, one an ICE vehicle and the other a battery EV, you find that the energy consumed by the ICE,

\(^{32}\)We use the term “round-trip” to emphasize that the starting and final energies are electric: whatever the process steps and conversions, it is always electric-to-electric energies. We stress that it is not the battery-to-wheels efficiency, which would include the motors, transmission, ..., and even less a more global efficiency taking into account still other effects, such as that of air-drag (which we assume to be model independent).

\(^{33}\)If we instead take an ICE vehicle with a tank-to-wheel efficiency of, say, 25%, the fuel demand for the ICE model (which is the dominant one represented in Table 1) would be 400% the final energy at the wheels. ICE is known to have low fuel-to-wheel efficiencies, but has been improving with time, and further improvements are expected in the future, which are taken into account below in our calculations.

\(^{34}\)Electric motors and transmission are much more efficient than the equivalent ICE technology. This is the reason behind a present estimate of an efficiency gain by a factor of about 2.5, if all ICE vehicles were substituted by battery electric ones. However, such a gain is not observed nor predicted for hydrogen powered electric vehicles.

Note that the efficiency of electric traction motor-to-wheels is taken the same for all electric transport models, and therefore is not model dependent. This is why we focused on the round-trip efficiency grid-to-motor, which is highly model dependent. (The significant difference is between battery EVs and H2 EVs; the difference between Plug-in and BSwap is second order, compared to H2 vs batteries.)
in the form of the liquid fuel, is about 2.5 times \(^{35}\) the electric energy the EV took from the grid. This factor represents the present global efficiency gain when comparing an average ICE vehicle fleet with a similar one of battery electric vehicles.

The hydrogen process is similar in concept: the efficiency of the hydrogen process also measures how much electric energy reaches the motor per unit of electric energy taken from the electric system, but with more complex steps because of the intermediate energy vector, hydrogen gas:

1. Electric system energy-to-hydrogen, at an electrolyser production plant. One can define many sub-steps, such as electric energy from grid to electrolysers, electrolysis, gas purification, compression, storage, and plant dispensing; and many other background processes, such as heating and cooling, or water purification, that must also be included. It is wrapped up as “hydrogen production”, and its efficiency is defined as the ratio of the chemical energy of H2 out of the plant and the electric energy consumed by the plant.

2. Hydrogen at plant-to-hydrogen in EV vehicle tank. Many sub-steps can be defined, such as hydrogen gas compression and/or liquefaction, distribution by pipeline, ship or truck, and, at the dispensing station, transfer, storage, and the complex dispense of hydrogen into the vehicle tank, typically compressed to 700 bar. This is wrapped up as “distributing and dispensing”.

3. Hydrogen in vehicle tank-to-electric energy at motors, the “tank-to-motor” step \(^{36}\). The heart of this step is the fuel cell, which converts the chemical energy of combining hydrogen with oxygen from the air into electric energy, which is then fed, via power electronics and controls, to motors, directly and via the battery (fuel cell vehicles need a large battery for drivability and peak power).

In contrast to current battery EVs, the round-trip efficiency of the hydrogen process \(^{37}\) is presently below 30%, and this would cause electric energy demand to be even higher than that for fossil fuel energy in Table 1, and the electric system would have to more than double its generation just to satisfy mobility. There is of course much research and development on hydrogen processes going on, much of it precisely on improving the cycle efficiency. However, this efficiency will always be limited in practice \(^{38}\), and the technical targets for the hydrogen cycle by 2050 point to round-trip efficiencies of the order of 50% \(^{39}\). Here we took an intermediate stage of H2 technology development, e.g. with a truck on-board average fuel cell efficiency not quite the ultimate target, but closer to it, and a

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\(^{35}\) From Tables 2.1 and 2.2, you get a value closer to 2 (1.84 for the heavy truck, 2.16 for the light vehicle). This results from the expected evolution of efficiencies by the reference year of the calculation (see Annex 3 for the model parameters). While battery EVs are already quite efficient, and so cannot improve much, ICE vehicles are so inefficient (in spite of significant gains in the past decades) that they are expected to improve more. This improvement is mostly forced by emissions regulations, which ICE automakers must meet in the future.

\(^{36}\) Similar to the classic tank-to-wheel efficiency concept, but note that it does not consider losses at the motor and transmission (which are much less with electric traction than in ICE vehicles).

\(^{37}\) We only consider the decarbonized process of obtaining hydrogen, via water electrolysis (which is bound by a theoretical limit of 84% LHV, if we discard the water vapor condensation energy). Present alternative processes use fossil fuels, namely natural gas. Another decarbonized process obtains hydrogen from biomass, but this is presently far from large-scale availability.

\(^{38}\) Unless of course a chain of disruptive technologies (a single one, in one of the processes along the chain, in not enough) becomes available, which is something we must not count on: silver bullets are very rare indeed. In Annex 2 we briefly touch on fuel cell efficiency.

\(^{39}\) See, for instance, the USA DOE or European technical targets for hydrogen. Interim efficiencies for the mid-term of fuel cells, electrolysers, etc. are rather lower.
THE TRANSITION
Why we need battery swapping for the future energy and transport systems

global round-trip efficiency of 37%, well above present. Even with this interim development of H2 technology, demand for energy from the electric system is 270% the demand at the motors, and about equal to present total electric consumption. We note that this energy consumption in H2 is more than double that of the most economical model, BSwap, and is actually higher than that of a diesel truck at the same future time, as can be seen in Figure 2.1 (which uses the data from Table 2.1) below.

Electric energy consumption differs also between the two battery EV models, Plug-in and BSwap, but this is a second order difference, which originates mainly from the unavoidable use of fast charging in Plug-in, which is totally absent in the battery swap BSwap model, which uses exclusively slow charging of the EV batteries.

In the next paragraphs, we shall describe and compare the four models from the points of view mentioned above. We opted to start by precising the definition of our BSwap model.

The reason for this is that while the other models have been the subject of much study and discussion, the BSwap model has been scantily considered so far; in fact, we don’t know of any proposal of a national decarbonization model similar to the one we propose here, and therefore it deserves a detailed definition, which includes the discussion of its roots, features and consequences. We shall then focus on the definition and on the discussion of differences between models, so that advantages or disadvantages become clear.

THE BATTERY SWAP MODEL

How to take advantage of the huge power on wheels

The idea of applying a battery swap model to a national system arose from trying to answer two questions: How can we use the huge power on wheels to help balance the grid? How can we solve the autonomy/time-of-charge problem of long-range travel, especially in heavy vehicles?

When we started thinking on the issues raised by decarbonization of the electric system and road transport, we were struck by the fact that not only energy demand for transport is generally higher than electric energy consumption, but also that the power capacity on wheels is outrageously high. The average power in the Portuguese national electric system is about 5.7 GW; how does power capacity on wheels compare with it? Let us perform a simple estimate: there are over 7 million vehicles on the roads in Portugal; if we multiply this by an average power capacity of on-board motors, say 80 kW, we get 560 GW, 100 times the average power in the grid!

Now if we are to substitute ICE motors for electric motors fed from batteries, the power capacity of batteries on wheels will be about the same. This means that if only a small percentage, say 10%, of vehicle batteries are connected to the grid while charging, they would have a nominal power capacity of about

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Another second order energy difference is more subtle: it originates in the way the electric system responds to the different ways each model procures energy from it. As we shall see when analysing the electric system, for one unit of energy procured from the system, there are differences in the required energy generation, due to the higher need for balancing the grid in the case of Plug-in than in the case of BSwap. These differences are not large; we shall show that the consequences are much more relevant on cost than on the amount of energy itself.

It can be obtained by dividing the annual energy consumption by the number of seconds in a year. If annual energy consumption is given in GWh, then just divide by the number of hours in a year. For instance, 50 TWh/year corresponds to an average power of 5.7 GW.

80 kW = 107 hp. A very small car may have only 30kW, but heavy trucks may reach over 500kW.
ten times the average power of the grid. This suggests they might (i) easily absorb any excess power generation in the grid, when the sun is shining and the wind blowing, and (ii) reversely, using battery-to-grid, help satisfy grid needs in times of scarcity.

In other words, they might play an essential role in solving the central problem of the future electric systems, imbalance.

The V2G (vehicle-to-grid) concept in the Plug-in model is based on similar ideas, also including flexibilization of the load to the electric system of vehicles battery charging. But it doesn’t work: the balancing impact on the grid is very limited with a Plug-in model. To understand why, accompany us in this thought:

I am the owner of a car, and 98% of the time my car is parked, so I can have its battery connected to the grid most of the time. However, most of this time the battery does not need any charge at all, because there is very little consumption; and I like to have the battery reasonably full, in case I need to go somewhere. So the only thing my battery can do is to cycle up and down, close to full charge, and this is a recipe for battery degradation for very little energy being exchanged with the grid. In other words, I might get a few euros per month with V2G, but pay more on expensive battery lifetime. On the other hand, when I travel, and use a lot of energy, I want to recharge immediately, and fast, not wait for the grid to have excess energy. So, I pay more for energy, and do no grid balance service.

Most of the battery capacity is on cars that consume very little. The opposite is true of heavy, long-range, trucks: a 40 ton truck may easily spend 50 times more energy than a car, because consumption per km is much higher, and because trucks are as much as possible on the road, not parked. So trucks, with a much smaller total battery capacity (because they are much fewer than light vehicles), have little time to service the grid, and most of the electricity that they need, they need it fast, along the highways.

The conclusion: whenever a realistic model for transport is used, the balancing effect of EVs on the grid has been very disappointing. This is why we started searching for a different model that might fare better.

How can we then take advantage of the large power capacity of charging batteries?

Simple: just decouple battery charging from vehicle use. In other words, let vehicles swap their low charge batteries for fully charged ones, which have been grid-connected in Battery Swap Stations (BSSs) for long charging hours, with plenty of time to wait for periods of excess generation in the system,
when electricity is cheap. This is the starting point of our BSwap model.

As we shall prove below, BSwap will connect charging batteries to the grid and have a dramatic effect on its balance. One interesting outcome is that most of this beneficial effect comes from turning the mobility load into a flexible one: batteries are charged at the most convenient times of the day from the grid point of view (and, once on board, the vehicle owner uses the battery unrestrictedly, at his own convenience). Bidirectionality, the ability to supply the system in times of power scarcity, is interestingly shown, in our specific system, to be a second order effect: load flexibility alone essentially solves the problem of grid balance (except, of course, in the case of grid incidents, when bidirectionality may play an important stabilization role).

In other words, from the grid point of view, batteries essentially do not act as storage devices, but rather as flexible loads.

Then, as we considered more deeply the outcomes of BSwap as the future mobility model for road transport, we realized that BSwap solves so many problems raised by the transition away from internal combustion engines that the only obstacle might be its cost. However, we prove below that, on the contrary, it is the overall lowest cost solution, beating easily H2, and cheaper also than Plug-in and even ICE (or much cheaper, if we include the special taxation of fuel in Europe).

**Extra batteries**

The BSwap model does need extra batteries for charging in battery swap stations (of the order of 10% of those on wheels), but, because battery lifetime is higher, in the end the need for (and the cost of) batteries may be less, not more, than in Plug-in.

One of the most common objections to the BSwap model is the perceived need for extra batteries. And the model does require more batteries, but the right question for cost is not

- how many more batteries do we need to have?
- how many new batteries must we acquire per year?

Once you consider the consequences of the BSwap model for battery lifetime and management, including the use of materials, you find out that most probably the global cost of batteries with battery swapping is less, not more, than with a Plug-in model.

One reason for this is that in BSwap batteries are slowly charged in a controlled environment, whereas with Plug-in fast charging is unavoidable, and in uncontrolled conditions. Now fast charging, particularly at high or very low ambient temperatures, is a major cause of battery degradation. So, we expect that battery lifetime will be higher with BSwap. In Annex 5, we assume a modest increase in average battery lifetime from 8 years with Plug-in to only 9 years with BSwap and demonstrate that this effect alone would more than compensate the need for extra batteries.

There are other reasons for lower global cost of batteries in BSwap, probably the most important of which is standardization, and high-volume fabrication (partly due to the expected acceleration of the shift from ICE to EVs with BSwap, because of mass consumer adhesion) that should cause production costs to fall. Still other reasons may be cited, such as the decoupling of battery lifetime from vehicle lifetime, the higher residual value of the battery at the end of its lifetime in BSwap, the lower need

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48 When a Plug-in vehicle is taken out of circulation, the battery might still be good for a couple of years, but the cost of ex-
for raw materials and higher recycling rate\textsuperscript{49}. However, none of these were included in the semi-quantitative cost analysis for model comparison, only the cited modest increase in lifetime.

**Feasibility**

*Technical feasibility is amply demonstrated.*

Past experiences of Tesla and Better Life/Renault proved that battery swapping is technically feasible, but their business model was wrong, at the wrong time. The most interesting present experiments are occurring in China, particularly with car maker NIO. It is a company that decided on battery swapping as corporate strategy, starting in 2018 with the intention to install 8 BSSs along the busy Beijing-Shanghai highway. As of April 2022, many millions of swaps had been performed, 800 BSSs had been installed, and NIO plans to reach 1300 BSSs by the end of 2022. One demonstration of the interest, to clients, of this battery technology: NIO announced in 2021 its fourth-generation battery, and (at least until now) new batteries have always been backwards compatible, which means that their old customers, with older EVs, may enjoy double the original autonomy range. Another good reason for their clients to feel satisfied, beyond the elimination of range anxiety.

The model we propose goes one step further: the BSwap model we propose is not the venture of a single country, or of a single brand. It will be based on universal standards, accepted by all the brands (that adopt it). And once a few of the prominent brands start collaborating on common standards\textsuperscript{50}, it will be difficult for others not to join.

**Infrastructure: Battery Swap Stations (BSS)**

*We detail a vision of future battery swap stations and estimate their cost.*

We don’t expect BSSs to be cheap, but the real issue is comparison with the alternatives. We do not have hard numbers to cite yet, because the technology is far from mature. (One guiding number is given by NIO, who claims that their BSS costs about 0.5 M€.) In order to estimate their cost, let us look more closely at what might be in a future BSS:

1. **Installation costs**

   We assume that most of these stations will be an evolution of present fuel stations into electric energy hubs. Much of the investment in land, civil construction (road access, buildings), licenses, exists already.

2. **Energy and power per BSS**

   There are presently 3,200 fuel stations in Portugal, and some 2,000 of these might become BSSs of various dimensions. An average BSS would consume about

   \[
   \text{Energy/day to BSS} = 60 \text{ GWh}/2\ 000 = 30 \text{ MWh/day}
   \]

\textsuperscript{49} Gains of up to 30\% are being predicted in scientific studies.
\textsuperscript{50} This is happening already, but with two-wheel vehicles. The most notorious example is the decision in 2021 by a consortium with brand names such as Honda, KTM, Piaggio and Yamaha to work towards common standards for a common battery swapping system. Once successful, few other brands will want to be left out of this venture. Among other interesting initiatives worth mentioning, Gogoro is a well known successful one.
and have permanently resident batteries with nominal capacity of 39 MWh (for 24h average residence time). The peak rate of charge is limited, in our model, to 0,3C\(^51\) (the normal maximum rate being 0,2C), so that the BSS operator may choose to charge its resident batteries using the 3,3 hours of each day with the lowest tariff (or, of course, spread the charging times over the day, according to convenience and energy price).

An interesting alternative for the BSS owner would be to hand over the control of the bulk of the BSS grid energy consumption to the system operator \(^52\), who would adjust supply at any time according to the convenience of system balance: the dream situation for the operator, with a large amount of 100% flexible consumption, plus firm power availability (battery-to-grid) in case of need, under his control. On the other hand, the BSS owner would benefit from the lowest energy prices: a win-win situation.

For a BSS of average size, the power capacity of the grid connection might be about 10MW\(^53\). Then all 2 000 BSSs could absorb from the grid practically any excess peak generation up to

\[
2 000 \times 10 \text{ MW} = 20 \text{ GW}
\]

which is double the expected average power of the national grid by 2050. Consequences:

- For the grid, curtailment or export of excess electric energy at low cost are no longer necessary.
- For the grid, when in need of support, a battery-to-grid firm power up to 20 GW\(^54\) can be dispatched, a power that far exceeds usually recommended back-up power. (Such a capacity, in practice, would not be installed; this large number means simply that battery-to-grid power capacity is not limited by battery capacity, and can be freely chosen for technical and economic reasons.)
- For the BSS operator, the energy is bought at the lowest tariffs of each day.

3. Battery chargers

Standardized battery modules do not have a standard capacity; on the contrary, as technology evolves, a standard module, while keeping constant its dimensions, will probably increase the amount of stored energy it can pack in. It is up to industry to decide what the most convenient initial capacity should be; about 40 kWh per module is probably a reasonable choice: a small light car would need only one, a SUV two, and a heavy truck might take twenty. The average number of resident battery modules in a BSS will then be

\[
\text{Number of resident battery modules} = \frac{39 \text{ MWh}}{40 \text{ kWh}} = 1 000
\]

\(^{51}\)1C is the rate of charge that would completely charge a battery in 1h; the power is numerically equal to nominal capacity, e.g. 10kW charging rate for a 10kWh capacity battery. 0,3C corresponds to a charging time of 3,33h, about one order of magnitude below present fast charging.

\(^{52}\)In practice, the BSS owner presents its needs and flexibility margins, plus the availability of further services. How exactly it may work depends on regulation.

\(^{53}\)The connection to the intermediate voltage distribution grid is of course taken into account in the cost structure of a BSS. On the connection power capacity: such high-power connections as were used in our model may prove unnecessary in practice, and lesser connections might be appropriate.

\(^{54}\)In practice, a much lower battery-to-grid capacity would be sufficient for grid stabilization, even considering serious rare events. In our battery-to-grid model in this work, we did not consider emergency situations, and limited B2G power capacity to only 3.7 GW, which was found more than sufficient for the regular action of system balance: the grid required a maximum power of only 2 GW from BSSs in our year-long simulations.
The number of chargers per BSS should be of the same order, so that all modules may be grid connected during their residence time. With such numbers, industry will probably design charging rack modules containing some 100 chargers each, some 6m wide by 3m tall, with all their power and control electronics. An average BSS would have 10 such modules 55, while the smallest might have only one. The number of chargers needed, at a national level, is about $2,000 \times 1,000 = 2$ million 56. How much will they cost? The number of chargers needed in the Plug-in model is less, but of the same order; however, there is a crucial difference: each public Plug-in charger needs a weather proof container, with civil construction mounting, an energy meter and billing capability with internet connection, plus a grid connection (shared with only a few other chargers), whereas BSS chargers are rack mounted, in a controlled environment, sharing a single electric connection with $= 1,000$ others, with no need for billing capability, and only internal electric connections. Also, while chargers for Plug-in come in a variety of power capacities and types of mounting, BSwap chargers are highly standardized, all the same power, with very high-volume production. All this suggests that BSwap chargers will be much less expensive than those for Plug-in.

4. Battery swap robots
These are a central feature of BSSs. Low charge batteries need to be extracted from the vehicle, and charged ones taken off the charger rack, transported to the swap spot, and inserted into the vehicle. Standards must be adopted, so they work with any vehicle brand. Particularly challenging will be the case of multiple battery module vehicles, such as heavy trucks: while for light vehicles most probably batteries will be accessed from below, how will it be in heavy trucks? From below as well, with stacked modules? Laterally, below or behind the cabin? Will one single robot be able to handle all types of vehicles, or it will be better to have two different types? How efficient and cost effective such robots will be depends much on the ingenuity of industrial designers. Present BSSs are illustrated by e.g. NIO’s, which demonstrate a swap time of a few minutes 57, and a capacity for over 300 swaps/day.

5. Overall cost of a BSS
There are many unknowns for sticking a price tag over an average cost for converting a fuel station into a BSS. NIO claimed an investment cost per BSS of only 0.5 M$ 58. Tentatively, we have used, for the model cost calculations, an informed guess of an investment cost of 4 million euros to convert an average present fuel station into a BSS (which we think might be an upper bound in the future).

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55 All these numbers for BSSs refer to a mature BSwap model. In earlier stages, particularly while full grid stabilization is not yet a requirement (e.g., because gas turbines still do much of the balancing), a small fraction of these numbers would be enough.
56 Worldwide, the number should be over a thousand million chargers.
57 Battery swaps taking 1 minute only have already been demonstrated.
58 On the field, the initial cost ran rather higher than this. We have no information on how costs evolved more recently, as BSSs are being produced in larger numbers.
Standards

Standards must be designed so they are accepted by industry and allow innovation.

This was one of our early worries: would standards get in the way of technology evolution? We are now convinced that correctly defined standards will not stifle innovation, and that the benefits vastly overcome the possible problems. But we underline the word “correctly”, which is far from trivial.

For instance, battery modules must have standard dimensions, electric contacts, and mounting process: all that regards their mechanical insertion and connection to vehicles. But they certainly should not have a standard energy capacity, while weight, voltage, battery system management, and power output capabilities might be only boundary restricted, within a broad range. Even the internal chemistry of batteries should not be standard restricted: the system needs to know its electric characteristics but may totally ignore what goes on inside: they could use lithium or sodium ions, electrodes made of phosphate or oxide, graphite or silicon carbide, whichever technology is proving good results at the time.

Communication of characteristics to chargers and vehicles should also be subject to standards. The reason for this is that modern power systems (chargers, or on-board electronics) easily cope with different batteries: all they need is to identify the type of battery that was connected, and load the appropriate algorithm for it, be it for the optimum charging strategy or on-board use of all its power and range capabilities. This requires intelligent power electronics, but electronic intelligence becomes very cheap at large scale. Also, even with broad standardization, it is easy to predict that a few different types of battery, with different prices, will be available at BSSs, from a premium to a low-cost type, or even specific branded ones. My conclusion is therefore that battery standardization will not stifle technological innovation.

But will industry accept it?

The automotive industry will probably be the most difficult to decide embarking into the battery swap venture. In fact, battery swapping goes exactly against present bets of most passenger car manufacturing industries: they hold on to their excellent batteries, design vehicles to incorporate their unique battery, and claim for chargers of ever higher power, needed for acceptable fast charging times. The automotive industry brands are presently too focused on owning their excellent, unique battery as a commercial competition weapon. However, this was justified at times of great battery immaturity; but will anyone think, in the future, say in 10 years’ time, that Toyota batteries are so much better than Volkswagen’s? Already in the present, a battery producing company such as CATL supplies BMW, GM, NIO, Tesla, VW, …; and one single company is said to produce 80% of all graphite-like cathodes. Automotive companies also have not realized (and may choose to ignore) the facts that energy will be much more expensive in Plug-in 59, and that the transition to low emissions will be much slower 60. The same is still true for part of the truck making industry, but we think that it will

59 For two reasons: (i) high power chargers will buy energy from the grid at regular industrial tariffs, rather than the lowest ones of BSwap, which uses only times of excess power generation availability in the grid and minimum cost; and (ii) the cost of electric energy with Plug-in will be generally higher than with BSwap, because of the cost of balancing such a grid, which has to support the large, mostly rigid, demand of e-mobility.

60 For two main reasons also: BSwap would accelerate the transition (i) to electric mobility (range and ease of use would encourage renitent owners of fuel powered or hybrid vehicles to switch to all-electric vehicles), and (ii) to a decarbonized grid: with the power of BSwap batteries grid-connected, it is much easier to integrate high proportions of variable renewables such as wind and solar, or even nuclear.
be easier for this sector of the industry to realize the immense benefits of the BSwap model for long-range road transport.

Once the convenience and advantages of battery swapping become apparent, and a few large brands announce they are making a consortium to define compatible, swappable, batteries\footnote{Motorbike companies were faster in realizing the advantage of battery swapping, in their case driven not because of energy cost considerations, but by convenience of use for satisfaction of their clients, and by sharing investment costs. One already old example is that of Gogoro, but perhaps a more significant one, similar to what we would expect to happen in the automotive industry, was initiated in 2021, with the formation of a consortium by Honda, KTM, Piaggio and Yamaha to develop a multi-brand, swappable battery system.}, few brands will dare be left out. This process could be much less expensive and orderly if public policy stimulates wide industry participation in defining standards that might become worldwide, as we discuss below.

When this starts to happen, many other stakeholders must reorganize for their own challenges, from the battery to the power electronics and control industries, from the owners of BSSs to grid operators and regulating institutions. This is one more reason why public policy will be crucial to accelerate and stimulate this complex transition.

**Quality assurance**

*Quality assurance is essential for consumer confidence.*

Consumer confidence is crucial for success of the BSwap model: will the battery I am inserting in my vehicle perform as stated? Or will this guy at the BSS make me pay for a premium battery, and hand me an old piece of junk? Quality certification of the battery and of the BSS are essential. How might it be realized?

Once a battery is inserted into a BSS charger, it starts being monitored, and checked against brand specifications, and there is no better way to do it than perform diagnosis over a complete charge cycle. If the battery is healthy, satisfying the minimum standards, it passes for vehicle use. If it fails, it is immediately sent for second life (if it is healthy, just not performing enough for vehicle use) or for repair or recycle (if degradation parameters indicate end of useful life). All this process is performed under certified algorithms, and the information must be product bound, be it via a battery chip, or in a data base, so that product tracking is possible and informative (as is presently done in many industries).

With such a quality assurance process in place, customers will trust the swapped battery, and benefit from technological evolution: vehicles are not stuck with their old batteries, owners may always have the best available in the market, or they can choose to accept a lower performing one, but equally certified, for a lower cost.

**Business models**

Businesspeople will have much higher competence and imagination than us in piecing together models for businesses. Our aim here is just to check how it may work from the points of view of a few stakeholders. We use only raw costs, with no margins (just a financial 6% rate, common to all calculations) or special taxes added (except in the case of ICE for fuel).

Just a note on the BSwap model: with battery swapping, there is no advantage in owning the battery: the cost would be higher, and the benefit of technology evolution lost\footnote{On the contrary, with the Tesla battery swapping model, the car owner had to hang on to his original battery, it just “borrowed” batteries while travelling, and had to go back and pick up “his” battery from the first BSS where he had left it. In our opinion, a wrong model, coherent with this idea of owning this unique, excellent battery as a personal cherished object.}. In our calculations below for
THE TRANSITION
Why we need battery swapping for the future energy and transport systems

BSwap, we assume batteries as a service, similar to refuelling in present fuel stations.

The upfront cost of a new vehicle in BSwap therefore does not include the batteries. We assume, as an example of a possible business model, that the buyer signs a contract with a monthly value that covers the cost of batteries, the cost of battery swap stations and a number of free swaps per month (according to commercial strategy). He may use home charging, if he so wishes (so customers feel they are not totally dependent on swapping, which is particularly useful while the BSS network is still modest), but the batteries are barred from fast charging\(^\text{63}\) (so that battery lifetime is preserved). In the swap station, he will pay nothing for the contracted free swaps; beyond the contracted swaps, he will pay a small\(^\text{64}\) fee for each additional swap service. If he prefers a premium battery, instead of the basic one, and this is not foreseen in the contract, he pays a further small fee for the upgrade in range and performance.

A short summary of the essential features of the BSwap model

It is assumed that in a near future, vehicle and battery manufacturers will have converged into universal standards for modular batteries, regarding both mechanical dimensions and mounting, and electrical connections. Capacity, power, voltage, or management systems need not be fully standardized: intelligent power systems will easily adapt.

Vehicles swap low charge batteries for charged ones at battery swapping stations. Most of these stations will be an evolution of present fuel stations into electric energy hubs, each equipped with about a thousand standard, certified (for quality assurance) battery charging units, and a few battery swapping robots (with ≈1min swapping capability); typical electric grid connection power capacity per swapping station is ≈10 MW. Ideally, modular batteries would be such that small light vehicles might use only one, while a heavy freight vehicle might need 20 modules, all identical in shape and interchangeable; however, this is not a model requirement: a number of different types of modular batteries might coexist.

Battery swapping stations become important nodes of the electric system, offering it

1. A distributed flexible load, amounting to 20 to 30\% of total electricity consumption, and
2. A distributed firm reserve power of the order of the average consumption power of the national electric system,
3. The external power management of which might be totally handed to the grid operator, offering the operator a powerful instrument to achieve grid stability and quality of service.

The BSwap model decouples battery charging from vehicle use; no fast charging is necessary, and electric grid balancing service is easily performed (mostly by turning battery charging into a totally flexible load) to the advantage of both the swapping station operator and the power system. Other major

\(^{63}\) This will be an imposition only in a mature BSwap model, when there are plenty of BSSs available. In earlier stages, this should not be imposed, of course, for the ease of use while BSSs have a low geographical density.

\(^{64}\) It should be small because his share of systemic costs (batteries, BSSs) is covered by the fixed value of the contract. It might be a fixed fee, say of the order of 10 € for a passenger car: the cost of energy, for a 600 km autonomy, would cost less than 4 €; the remaining 6 € would cover marginal use of the infrastructure, and tax. (We foresee no specific payment for the exact energy because its deviations from average are negligible and would not justify the complication of a billing procedure – too small to meter.)

Note that the 10 € fee is less than you would pay for home charging: at a 0.20 €/kWh home tariff, the same additional autonomy would cost about 19 €. This would encourage replenishment at BSSs, of course. In practice, commercial strategy will decide this fee.
advantages of the BSwap model are the ease of electrification of heavy long-distance transport, and the foreseen acceleration of transport decarbonization since vehicle refuelling is as simple as in the present. Finally, we anticipate it will be the overall lowest cost model, part of the reasons for this being discussed below.

The concrete BSwap models considered here assume an average residence time of batteries in swap stations of one day and of two days (in this latter case with 75% of them being swapped within 24h), and a maximum charging rate of 0.3C (or 0.3 kW/kWh, slower than present fast charging by one order of magnitude). While charging, batteries act as a flexible load. The effect of a mild battery-to-grid capability was tested in the model, with a maximum discharge rate of 0.1C (equivalent to 10h to discharge), and permissible only for batteries with states-of-charge such that they are least affected by cycling. (However, this function of up and down energy from the grid will probably be performed instead by second-life batteries, while energy flow for charging EV swapable batteries will be unidirectional.)

THE PLUG-IN MODEL

In our Plug-in model all vehicles are battery electric and get their energy by plugging the vehicle to a charger connected to the grid.

The problem of charging time

One of the major problems of substituting ICE vehicles by Plug-in becomes apparent when we calculate the power connection of a fuel hose. When we refuel, the flux of fuel is about 1 litre/s, and 1 litre of fuel contains roughly 10 kWh of energy\(^6\). The power of the connection is then

\[
\text{Power} = \frac{\text{Energy}}{\text{time}} = \frac{10\text{ kWh}}{\text{s}} = 36\,000\text{ kW} = 36\text{ MW}
\]

For the unfamiliar reader, this is the same order of magnitude of the average net hydroelectric power of some of Portugal’s largest dams, such as Castelo do Bode or Alqueva\(^6\), or the average electric power consumption of 80,000 families!

The problem of charging time for an EV becomes apparent: such electric power out of a socket is unthinkable.

Fortunately, EVs are more efficient than ICE vehicles, say by a factor of 2.5; then the power needed for electric charging gets divided by this number. Obviously, we still must spread the time for electric refuelling in order to lower the power; it takes about one minute for diesel, but if we do not mind waiting half an hour for charging up, we may load in the energy necessary for the same range in the EV with a charger with a power capacity of

\[
\text{Power of charger} = \frac{36\,000\text{ kW}}{(2.5 \times 30\text{ minutes})} = 480\text{ kW}
\]

\(^6\) In this discussion, we use orders of magnitude, so that the issues are not lost on details.

\(^6\) Note that we are talking about average power, obtained by dividing total annual net energy generation, from water fluency into the dammed lakes, by the number of seconds in a year. This actual average generation power is much smaller than the installed power capacity, which is hundreds of megawatts in both hydropower units – but mostly idle along the year. Presently, this capacity is becoming more and more active, but mostly for pumped water rather than natural flow, a possibility that was introduced in recent years. There will be more water cycling up-and-down the dams than the natural flow.
Of course, if we accept that the range of an EV be only 30% that of an ICE, and that in a fast charge we only reach 80% of battery capacity, then the charger power needed comes down to 115 kW, precisely of the order of many current fast chargers.

Note that, even if limitative and bound to cause range anxiety, Plug-in is not an insurmountable hurdle for many urban drivers of light EVs. However, how can it apply for long-range travel of heavy trucks? It is not impossible, but so limitative that it is hard to make commercial sense.

**Energy efficiency and cost**

Efficiency wise, Plug-in, benefiting from the high efficiency of modern batteries, is at least twice as efficient as H2, and just a little worse than BSwap, mostly because of the need for fast charging, and the corresponding higher losses.

In spite of its high energy efficiency, you may notice that the cost of energy for a light Plug-in vehicle is 58% over that for inefficient H2, and four times that for BSwap (Table 2.1). The reason is that much of the energy used in Plug-in is affected by home or regular industrial electricity tariffs, and grid management possibility (load flexibility and V2G, namely) is very limited, contrary to H2 and BSwap, which adapt to grid needs (or may use dedicated renewable sources). We used for heavy vehicles a cost of energy of 100 €/MWh (close to average industrial tariffs) and 150 €/MWh for light vehicles (with higher weight of low voltage tariffs, such as home charging).

**Infrastructures: chargers**

A positive point for Plug-in is that it has the lowest estimated cost of infrastructures among the EV models. Plug-in chargers are not cheap, but we estimated they would be cheaper than battery swapping stations, and very much cheaper than the infrastructures for production, storage, compression, distribution and dispensing of hydrogen.

**Costs**

Batteries weigh a lot in the acquisition cost of a new Plug-in vehicle, the reason being that despite a decreasing price of batteries, (1) we still assumed a conservative value of 70 €/kWh capacity by the reference year, and (2) we assumed a battery capacity per vehicle much higher than common at present: the level playing field required that all vehicles, ICE, H2, Plug-in or BSwap, should have the same range. The result is that batteries weigh 28% in the cost of a new light EV and 42% in the case of a heavy truck, making new vehicles, within our Plug-in model, the most expensive.

On the other hand, once you take away the cost of the new vehicle, Plug-in light vehicles reveal the lowest yearly cost for a light vehicle, and on a par with BSwap for heavy trucks.

In the global cost per year, in our model, by the reference year, Plug-in vehicles, both light and heavy, are already cheaper than ICE and H2, second only to BSwap.

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67 We assumed 70 €/kWh, probably an upper bound by the time of the reference year of this study, because the cost of EV batteries has been falling at a rate much higher than predicted only a few years ago: in 2020, the average price cited by Bloomberg’s New Energy Finance was already 137 US$/kWh. Even when we take the usable, rather than the maximum energy per battery (which is of ~90%), we still get an average value of 130 €/kWh, with the lowest values as low as 96 €/kWh, a more than 20% decrease from the previous year. In 2021, the USA Department of Energy, as other institutions, also dropped its target from 100$/kWh to 80$/kWh, and automotive brands such as Volkswagen are already mentioning future prices of 60 $/kWh. A warning: it is expected, in this as in any other maturing technology, that materials prices will suffer from high growth of demand, as is starting to happen now. However, in the longer run, markets and supply chains will adjust, and prices decrease.
THE H2 MODEL

In the H2 model all vehicles run on green hydrogen, which they get at a dispenser. Hydrogen is an energy carrier, which is produced by electrolysis with electric energy obtained from the grid and/or dedicated renewable generation.

The problem of fuel cost

One of the major problems of substituting ICE vehicles by hydrogen powered EVs is fuel cost. This problem may be divided into the energy efficiency problem, discussed in the next section, and the cost of the infrastructures necessary to dispense hydrogen to fuel-cell electric vehicles, which we discuss here.

We used in this work mostly the interim targets of the USA Department of Energy for hydrogen mobility \(^68\), coherently with our choices for all the other models. We used a cost for capital and O&M for an electrolyser plant of only 0.33 €/kg H2/year, but once one considers all the infrastructure and processes hydrogen has to go through until on board, in the high-pressure tank, the cost just goes higher and higher: the final cost for production, compression, storage, distribution and dispensing came out as 4.3 €/kg H2; in this work, we arbitrarily opted for a lower value, 3.5 €/kg H2, by the reference year.

Energy efficiency

The second part of the problem of hydrogen fuel cost is the low round-trip energy efficiency.

We assume that technology evolution leads to higher efficiencies. For instance, hydrogen consumption by a mid-class passenger vehicle was assumed as 0.8 kg of hydrogen/100 km (see Annex 3), implying an efficiency improvement of 25% from present state-of-the-art.

However, even with a high efficiency electrolyser, and 65% efficiency for the fuel cell in a truck, which we hope will be achieved in the medium term, the whole process ends up with a global efficiency of only 37%, well above present but insufficient for low costs. And it is by no means evident how the ultimate goal of 50%, which we used in the study of the impact on the electric system by 2050, may be economically reached.

With the values cited above, the on-board efficiency of a fuel cell truck is higher than that for an ICE: its energy consumption is about 80% that of a diesel-powered truck \(^69\), but once one considers the whole cycle, starting at the hydrogen production plant (the round-trip efficiency), the energy consumed by a fuel cell truck is actually 35% above that of the equivalent future ICE truck.

Power module costs

The costs for the on-board power module were also obtained from the medium-term interim targets for components such as hydrogen tanks and fuel-cells and are much lower than present. In fact, if

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\(^68\) The so-called “ultimate targets” for H2 are not technically driven, they are confessedly obtained by reverse calculation, namely: Which must be the H2 costs so it becomes competitive with ICE? They are not driven by technical expectations, and therefore are not usable here. The choice was the same for the other models: interim technical and cost targets for the medium term were our option.

\(^69\) The difference in efficiency is lower than usually cited, because by the time of this study (2030’s) diesel motors should achieve interim targets that make them rather more efficient than today’s average also.
these targets are achieved, our calculation foresees that the cost of a H2 truck is just a little higher than a diesel one, and much lower than a Plug-in. However, it would still be 28% more expensive than a BSwap truck (because the cost of a BSwap truck does not include the batteries).

To compare similar vehicles, we assumed similar power for each class. For the heavy truck, the ICE motor and the electric motors were chosen with nominal power of 500 kW. The case for H2 deserves special mention: we assumed a choice which we think is virtuous in terms of cost and performance: the fuel cell has only 300 kW, the peak power is reached via the 100 kWh batteries on-board. This should generally compare reasonably with the 500 kW power modules of the other models on the grounds of drivability and performance.

Global cost

Once we add all contributions, the cost of a H2 heavy vehicle is the highest, still 17% over an ICE and 66% over the lowest, BSwap.

THE ICE MODEL

Road transport powered by internal combustion engines (ICE), running mostly on liquid fuels, is the incumbent model, that will be used as a benchmark against which the alternatives will also be compared.

The values used for ICE are coherent with the choices for the other models, namely for efficiency of ICE motors and air drag design: we used mid-term interim targets, not present values. As for fuel, we used the relevant cost from the point of view of a vehicle owner, a possible retail price in the future (similar to that of recent years, a large fraction of which is due to special taxes) of 1.30 €/l.

When discussing the global sector cost, we used both this value and 0.65 €/l, which might represent a cost of fuel production in Europe without special taxes.

RESULTS: COMPARISON OF THE ICE, H2, PLUG-IN, AND BSWAP MODELS

We now estimate and compare the costs that result from application of each of the models to the simplified road transport system of our case study, the idealized level playing field for the comparison of model outcomes.

The most relevant parameters for our calculations of costs for road transport within each of the models are shown in Table A3.1 for a heavy truck (tractor and trailer), and in Table A3.2 for a mid-class light vehicle, in Annex 3.

Definition of the simplified road transport system

As stated before, the future system we use to test the different results from the four models, is inspired in Portugal, for concrete numbers on energy consumption (total fuel consumption for road transport in Portugal, 2019, was 65.3TWh) and number of vehicles (about 7.2 million vehicles, still
growing in all classes, but especially on heavy vehicles, a worldwide tendency). The present fraction of energy consumption due to light and heavy vehicles is about 60% and 40%, respectively.

1. We assume the road transport pattern and vehicle fleet are the same for all models. Range and power per vehicle were adjusted to be similar for all as well.

2. Final energy demand for road transport is 20 TWh in the reference year, defined as the
   a) Electric energy measured at the electric traction motors, in all EV models (H2, Plug-in, BSwap).
   b) Mechanical energy measured at an equivalent point, close to the wheels, in ICE vehicles.
      (Comparison with the electric models uses the future expected consumption of ICE vehicles in litres of fuel per 100km.)

3. The market is maturing, with assumed 6% expansion per year.

4. Technologies are maturing, with an annual decrease in costs of 1%.

5. We assume a vehicle fleet different from the present in the following aspects, which are justified by present trends and a vision of a future system shared by many in the field:
   a) The total number of vehicles decreases from the present 7 to 6 million vehicles.
   b) This decrease is mostly due to a decrease of private passenger light vehicles, whereas an increase of shared light vehicles and heavy vehicles is assumed.
   c) Energy consumption was assumed to be divided into 50% for all light vehicles, the other 50% being affected to heavy vehicles (justified by verified present trends).

**Points of view: The owner of a 40-ton truck**

BSwap strikingly outperforms all other models for heavy freight.

Whenever a transition is to occur, the point of view of the stakeholders is crucial, because individual decisions may shape the future. We start by considering the point of view of the owner of a heavy, 40-ton tractor.

Costs are seen from this micro perspective, but include their share of all system costs, which are included in the bill the owner must pay. For instance, in the Plug-in model we include the cost of charging points; in the H2 model, the cost of hydrogen production, distribution, and dispensing; in the BSwap model, the cost of batteries and of battery swapping stations; and, in all of them, the costs and benefits to the electric system. This last cost is accounted for in a simplified way, through a guessed, arbitrarily fixed, cost of the electric energy used in supplying grid-to-transport. This cost of energy is essentially an instrument of partitioning costs and benefits between the transport and power sectors, and might be refined later, when considering the electric system (Chapter III), but does not affect our conclusions when the coupled transport and power sectors are taken together (Chapter IV).

The inclusion of system costs is visible under the entries “Energy related costs” of Table 2.1. These include

- all on-board items required to power the vehicle (such as motors and transmission, but also fuel cells, batteries, power controls), and
- all off-board items required to bring energy to the vehicle (from hydrogen electrolyzers to Plug-in chargers to battery swap stations).
In other words, the following data refer to a single truck, but with all the system costs, calculated within each model, reflected in the cost structure of the truck, proportionally to its share of the global energy consumed by road transport.\(^70\)

The results of our calculations for the energy consumption and the costs of a 40-ton truck, for each of the mobility models, are shown in Table 2.1. The model parameters are given in Table A3.1 of Annex 3.

The basis for annualized investment costs was a 6% rate, and 8 years depreciation for trucks and 15 years for infrastructures.\(^71\) For instance, the investment cost of the basic vehicle, 50 000€ (Table A3.1), corresponds to an annualized cost of

\[
(\text{Annualized cost of basic vehicle}) = 0.1610 \times 50000 = 8050\text{€/year}
\]

as shown in the first row of Table 2.1.

One important factor in the decision to buy a truck, beyond its annualized cost, is the upfront cost the buyer must pay, which is shown in the lower appendix of Table 2.1. The upfront cost of an ICE truck includes the costs of the basic vehicle (50 000€) and of the power module (motor, transmission, ..., estimated as 65 000€), the total being therefore 115 000€. The large difference in upfront cost of a Plug-in (165 000€) and a similar BSwap truck (95 000€) is due to the batteries: with Plug-in you must pay for the batteries when you buy the vehicle, with BSwap you don’t: you pay for them as a service, through the payments for battery swaps. This is the reason the upfront cost of a BSwap truck is the lowest, even lower than that for an ICE truck, as shown in the lower part of Table 2.1 and represented in Fig 2.1 (blue bars).

It may surprise you at first sight that, once the upfront cost is paid, then the annual costs of a BSwap truck are also the lowest, almost the same as for a Plug-in truck (very last row of the lower appendix of Table 2.1, and represented in Figure 2.1 by the orange bars): how come, if these costs must include the batteries and infrastructures? The reason is the large difference in the cost of energy: energy is much cheaper for centralized charging at a BSS than for a public or home charger. Within our models, it is just coincidental that, for such a truck with high annual energy consumption, the addition of the annual costs is almost identical for a BSwap or a Plug-in truck (this is not the case already for a light vehicle, as may be seen below).

---

\(^70\) The share of energy consumption was used as the basis for partition of costs among the different classes of vehicles, including for instance the cost of batteries in the BSwap model. An exception to this rule was made in the cost of infrastructures: it would be unfair for heavy trucks to pay for the cost of, say, all BSSs, proportionally to their energy consumption, since trucks would not use most of the smaller, town-bound, BSSs, which do not even have the swap robots for heavy vehicle battery racks. They do pay for all the BSSs they use, mostly along the main highways or in logistic hubs. The other classes of vehicles pay for all the rest of the infrastructure costs.

\(^71\) The financial coefficients were therefore 0.1610 (8 years depreciation) and 0.1030 (15 years) and used in the formula Annual cost = coefficient x capital investment.
Why we need battery swapping for the future energy and transport systems

### The Transition

<table>
<thead>
<tr>
<th>Energy consumption per truck.year</th>
<th>Total cost per truck.year</th>
<th>Total cost per truck.km</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWh/year</td>
<td>€/year</td>
<td>€/km</td>
</tr>
<tr>
<td>ICE</td>
<td>H2</td>
<td>Plug-in</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Basic vehicle</td>
<td>8 052</td>
<td>8 052</td>
</tr>
<tr>
<td>Repair &amp; maintenance</td>
<td>12 500</td>
<td>9 400</td>
</tr>
<tr>
<td>Energy</td>
<td>278</td>
<td>219</td>
</tr>
<tr>
<td>Total (Fuel-to-Vehicle, Grid-to-Vehicle)</td>
<td>278</td>
<td>374</td>
</tr>
</tbody>
</table>

### Energy related costs

<table>
<thead>
<tr>
<th>Off board</th>
<th>On board</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power module (Motors, transmission, fuel cells, tank, ...):</td>
<td>10 467</td>
</tr>
<tr>
<td>Batteries:</td>
<td>1 127</td>
</tr>
<tr>
<td>H2: Grid to vehicle (production, distribution and dispense):</td>
<td>29 211</td>
</tr>
<tr>
<td>Plug-in chargers (cost of installed chargers + OR&amp;M):</td>
<td>3 922</td>
</tr>
<tr>
<td>Battery Swap Stations (chargers, robots, grid connection, OR&amp;M, ...):</td>
<td>8 423</td>
</tr>
<tr>
<td>TOTAL</td>
<td>278</td>
</tr>
</tbody>
</table>

| Upfront acquisition cost: | 115 000 | 121 131 | 165 000 | 95 000 |
| Annual cost: (annualized upfront cost not included) | 46 170 | 53 562 | 30 001 | 30 310 |

**TABLE 2.1** Comparison of the 4 models (ICE, H2, Plug-in, and BSwap) from the perspective of the owner of a 40-ton truck. The annualized costs of the basic vehicle, repair & maintenance, energy, and all energy related costs (required to power the vehicles) are shown in the central columns of the main Table. In the lower section of the table, the upfront cost of a new vehicle and the annual costs to run it are shown. Fuel cost for ICE is 1.30 €/l.

The conclusion is that the BSwap model outperforms all the others with the lowest total yearly costs (last row of the main body of Table 2.1):

- ICE is 42% higher, with fuel at 1.30 €/l (64.689 vs 45.608); at 0.65 €/l, ICE would still be 2% higher than BSwap.

While batteries and infrastructure (battery swapping stations) are expensive, the cost of energy in BSwap is so much lower than in ICE that it more than compensates the zero-cost accounted for ICE infrastructures (the existing service stations, with all costs covered already by the retail price of fuel). The lower maintenance cost of electric traction also helps, of course.
• H2 is 58% higher.
The main reason for this is not vehicle cost (as it would be presently); in fact, in this future model, a H2 truck would be less expensive than a BSwap truck with batteries included. The main reason lies in the difference in energy consumption and in the cost to get it on-board a H2 truck.

• Plug-in is 24% higher.
The main reason for this is the cost of electric energy. While in the BSwap model energy demand is totally flexible, and will therefore be bought at times of excess, thus helping balance the grid, which reflects in lowest prices for energy, in the Plug-in model energy is paid at the regular industrial rate.

BSwap also demonstrates the lowest upfront acquisition cost: only 83% of an ICE vehicle, and even cheaper when compared to H2 and Plug-in, as is also displayed in Figure 2.1.

![Costs for a 40t truck](image)

**FIGURE 2.1** Comparison of the upfront cost of acquisition and annual costs for energy, repair, and maintenance, for a 40-ton tractor, for each of the mobility models. (Infrastructure costs, and the cost of batteries in the case of the BSwap model, are included in the energy costs.) ICE fuel cost considered here is 1.30 €/l.

We note a point that is not reflected in these values: H2 and Plug-in trucks will need battery and fuel cell replacements during their long lifetime. These costs are not accounted for here, because this calculation is only for an 8-year vehicle depreciation and running costs (and we assume that by the reference year Plug-in and H2 truck batteries last for 8 years); but they would increase the difference
to BSwap even further if the whole lifetime were considered. These costs will be accounted for below, when we compare the global sector costs of road transport.

Points of view: The owner of a light vehicle

**BSwap demonstrates lower costs than all other models for a light passenger vehicle.**

For a light EV owner, contrary to the case of a heavy truck, energy is not the major contribution to cost, nor the highest owner priority when buying a new vehicle.

The results of our calculations for the energy consumption and the costs of a light passenger vehicle, for each of the mobility models, are shown in Table 2.2. The model parameters are given in Table A3.2 of Annex 3.

<table>
<thead>
<tr>
<th>Energy consumption per vehicle, year MWh/year</th>
<th>Total cost per vehicle, year €/year</th>
<th>Total cost per vehicle, km €/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE</td>
<td>H2</td>
<td>Plug-in</td>
</tr>
<tr>
<td>Basic vehicle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.255</td>
<td>2.255</td>
<td>2.255</td>
</tr>
<tr>
<td>Repair &amp; maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.000</td>
<td>750</td>
<td>500</td>
</tr>
<tr>
<td>Energy</td>
<td>On board</td>
<td>4.1</td>
</tr>
<tr>
<td>Total (Fuel-to-Vehicle, Grid-to-Vehicle)</td>
<td>4.1</td>
<td>4.6</td>
</tr>
<tr>
<td>Energy related costs</td>
<td>On board</td>
<td></td>
</tr>
<tr>
<td>Power module (Motors, transmission, fuel cells, tank, …)</td>
<td>1.288</td>
<td>1.517</td>
</tr>
<tr>
<td>Batteries</td>
<td>113</td>
<td>1127</td>
</tr>
<tr>
<td>H2: Grid to vehicle (production, distribution and dispense)</td>
<td>357</td>
<td>0.036</td>
</tr>
<tr>
<td>Plug-in chargers (cost of installed chargers + OR&amp;M)</td>
<td>135</td>
<td>0.014</td>
</tr>
<tr>
<td>Battery Swap Stations (chargers, robots, grid connection, OR&amp;M, …)</td>
<td>103</td>
<td>0.010</td>
</tr>
<tr>
<td>TOTAL</td>
<td>4.1</td>
<td>4.6</td>
</tr>
</tbody>
</table>

**TABLE 2.2** Comparison of the 4 models (ICE, H2, Plug-in, and BSwap) from the perspective of the owner of a light passenger vehicle. The annualized costs of the basic vehicle, repair & maintenance, energy, and all energy related costs (required to power the vehicles) are shown in the central columns of the main Table. In the lower section of the table, the upfront cost of a new vehicle and the annual costs to run it are shown.
The conclusion is that the BSwap model demonstrates the lowest total yearly costs for a light vehicle also, although as expected with smaller margins than for the case of a truck:

- **ICE is 12% higher**, with fuel at 1.30 €/l; at 0.65 €/l, ICE would be 2% lower than BSwap. Even with the high cost of batteries and infrastructure (battery swapping stations), the higher cost of energy and maintenance in ICE justifies its higher cost relative to BSwap.

- **H2 is 14% higher.** Again, the main reason for this is not vehicle cost (as it would be now): if we include battery cost, a H2 light vehicle could be slightly less expensive than a BSwap equivalent vehicle, in this future model. The difference results from energy consumption, maintenance and H2 infrastructure costs.

- **Plug-in is 9% higher.** This higher cost results from a combination of the costs of energy, batteries, and infrastructure (the higher cost of infrastructure relative to the truck case results from the high number of chargers of medium and high power that are used by light vehicles, but not by trucks).

BSwap also demonstrates the lowest upfront acquisition cost: only 82% that of an ICE vehicle, and even cheaper when compared to H2 and Plug-in, as displayed in Figure 2.2.

**FIGURE 2.2** Comparison of the upfront acquisition cost (blue bars) and yearly costs for energy, repair and maintenance, for a light passenger vehicle (orange bars), for each of the mobility models. (Infrastructure costs, and the cost of batteries in the case of the BSwap model, are included in the energy costs). ICE fuel cost considered here is 1.30 €/l.
The additional notes we made for the case of trucks apply here as well.

Points of view: The infrastructure owner and service provider

The service provider must charge higher costs to H2 customers than to BSwap or Plug-in customers.

Let us assume here (although it will not the case, in an evolved market) that a single company owns the services EV owners need: Battery swap stations and batteries, Plug-in chargers, or H2 production and dispensing infrastructures, and has to produce or procure energy and sell it (in the form of hydrogen, electric power, or charged batteries) at the infrastructure retail service points. In order to be solvent, how much does it have to charge its clients?

Simply by consideration of the relevant items in Tables 2.1 and 2.2 above (referring to a truck and a light vehicle) and of Table 2.4 below (referring to the global road transport sector), we conclude that the costs charged to clients within the BSwap model are far lower than those within H2. The reasons are that the cost of infrastructures, batteries, and of the energy to charge them, in the BSwap model, is lower than equivalent services in the H2:

- In H2, infrastructure and energy are far more expensive than in BSwap (although the tariff of primary energy was set the same for H2 and BSwap, the inefficiency of the H2 cycle means a lot more primary energy is consumed per final energy delivered).

The difference in service cost between BSwap and Plug-in is not so obvious; the conclusion is that this service cost is quite a par for both models, as justified here:

- In Plug-in, the cost of batteries is similar to that in BSwap (see Table A5.1 in Annex 5), but in BSwap it is included as part of the service, while it is paid for as part of in the upfront cost of a Plug-in vehicle. Also, infrastructures were estimated as cheaper in Plug-in than in BSwap. These two components would make BSwap service more expensive than that of Plug-in, but the difference is almost cancelled by the higher cost of energy in Plug-in. Although the amount of primary energy needed is only slightly superior in Plug-in than in BSwap, its cost is much higher, because in Plug-in it is the ordinary tariff for industrial electricity (or a combination of this and the home consumer tariff, in the case of a light vehicle with partial home charging), whereas in BSwap energy is bought at the very lowest prices. Interestingly, these two contrary effects nearly compensate, and the total cost of service with Plug-in ends up similar to that of BSwap.

Points of view: The road transport sector

The battery swap model strikingly outperforms all other models when we consider the global transport sector costs for new vehicles, power items, repair and maintenance, energy, and dedicated infrastructures.

This is a macroscopic point of view that is most relevant for a country, as it compares the global sector costs for each of the alternative models.

For model comparison, we assumed the same mobility pattern for all four models, with the same energy consumption at the traction electric motors of 20TWh/year, and an equivalent consumption for ICE. In
the ICE model, the same mechanical energy at the wheels resulted in a consumption of 52 TWh of fuel \(^2\), a tank-to-wheel global average efficiency of 37\%, higher than present, coherent with targets for the sector.

This reduction of energy consumption from present \(^3\) is expected to be a consequence of

a) higher vehicle efficiencies (from both mechanical and air drag changes), and a
b) change in mobility patterns,
c) even if global mobility increases (e.g. due to the rise of autonomous driving).

We shall not go deeper into this discussion, because the conclusions of our model comparison are not affected by the details of how mobility might be expected to change: the results of our calculations do change, but only slightly, with mobility patterns. The most relevant differences originate in the technological (ICE, H2, Plug-in, and BSwap) basis of mobility, not in its details. Therefore, we concentrate on maintaining a level playing field for model comparison and discard the effects of the details of mobility patterns.

Coherently with our aims of distinguishing models, the items considered for this sector cost study are those that are most affected by our different models, namely

- New vehicle cost
- On-board power items not included in the cost of new vehicles:
  - Replacement batteries and fuel cells in hydrogen powered vehicles;
  - Replacement batteries in Plug-in vehicles;
  - All the battery fleet in battery-swap vehicles.
- Repair and maintenance
- Energy
- Infrastructures:
  - None for ICE, since the cost of fuel service stations is already accounted for in the fuel cost
  - H2 production, storage, compression, distribution, and dispense facilities
  - Plug-in chargers
  - Battery swap stations

We used two values for fuel cost in ICE:

- 65 €/MWh, representative of fuel cost in Europe without special taxes, and
- 130 €/MWh, representative of retail price in Europe.

When considering sector costs, 65 €/MWh would be more appropriate, since it represents a probable future financial cost of fuel production, distribution, and dispensing. However, if we add external costs (impacts to the environment, to the economy, ...) \(^4\), then the 130 €/MWh gives an idea of how inclusion of such externalities would reflect on the model comparison.

\(^2\) The fuel consumption in this ICE model, 52 TWh, should be compared with that observed in Portugal 2019, 65.3 TWh.

\(^3\) The models are studied here at a time when the electric technologies are not fully matured, and have displaced most, but not all, of the old ICE mobility (remember the 6\% annual EV increase and 1\% cost decrease assumed in all EV models), which meanwhile is assumed to have evolved to higher efficiency as well. Therefore, we are not stating that the reduction to 70\% of 2019 fuel consumption derives purely from the reasons above. This does not bias model comparison, our assumed requisite, because all models are applied to the same level playing field.

\(^4\) And political incentives for a faster change. We are not claiming that the higher value reflects external costs.
The results are presented in Table 2.3. and Figure 2.3.

The aim of our calculations is to estimate the cost differences between models, which are explicitly shown in the last rows of the table.

<table>
<thead>
<tr>
<th></th>
<th>ICE Fuel 0.65 €/l</th>
<th>ICE Fuel 1.30 €/l</th>
<th>H2</th>
<th>Plug-in</th>
<th>BSwap</th>
</tr>
</thead>
<tbody>
<tr>
<td>New vehicles</td>
<td>17 250</td>
<td>17 250</td>
<td>18 701</td>
<td>19 580</td>
<td>14 130</td>
</tr>
<tr>
<td>Power items not in new V. (Batts, …)</td>
<td>0</td>
<td>0</td>
<td>2 723</td>
<td>2 109</td>
<td>7 583</td>
</tr>
<tr>
<td>Repair &amp; Maintenance</td>
<td>8 332</td>
<td>8 332</td>
<td>6 253</td>
<td>4 166</td>
<td>4 166</td>
</tr>
<tr>
<td>Energy</td>
<td>3 003</td>
<td>6 006</td>
<td>2 319</td>
<td>3 373</td>
<td>939</td>
</tr>
<tr>
<td>Infrastructures</td>
<td>0</td>
<td>0</td>
<td>4 531</td>
<td>975</td>
<td>1 274</td>
</tr>
<tr>
<td>TOTAL</td>
<td>28 585</td>
<td>31 588</td>
<td>34 527</td>
<td>30 203</td>
<td>28 093</td>
</tr>
</tbody>
</table>

Difference to lowest (M €/ year) | 493 | 3 496 | 6 434 | 2 110 | 0

Difference/GNP | 0.2 % | 1.6 % | 3.0 % | 1.0 % | 0.0 %

**TABLE 2.3** Comparison of transport sector costs within models ICE, H2, Plug-in and BSwap. Units are M€.

In Figure 2.3 the same results are displayed with items rearranged into:

- Cost of vehicle (annualized), which includes all on-board power items for the vehicle life, even if they are not part of the upfront cost of a new vehicle, such as the batteries in BSwap, and lifetime replacement of batteries and fuel cells in Plug-in and H2;
- Energy, repair and maintenance costs, where energy includes the cost of energy itself plus the cost of all the infrastructures that are needed to deliver energy to the vehicle.
- The difference in total cost for each model to the lowest, BSwap.

The main conclusion is that, at the level of a national road transport sector, the costs with the BSwap model are quite a par with ICE at the lower cost of fuel at 0.65 €/l, and lower than with Plug-in and outstandingly lower than with the H2 model:

- Lower than H2 by 6.4 thousand million euros per year (3.0 % of present Portuguese GNP)
- lower than Plug-in by 2.1 thousand million euros per year (1.0 % of present GNP).

Let us analyse the main reasons for such differences. If we take the sum of the first two rows (the cost of new vehicles plus the on-board power items not included in the new vehicles, such as batteries in BSwap), the blue bars in Figure 2.3, the result is strikingly similar for H2, Plug-in and BSwap. The differences result from the combination of the other three items considered, Repair and Maintenance (which penalizes H2), Energy (which penalizes H2 for its inefficiency, and Plug-in for its very limited capacity to make energy demand flexible), and Infrastructure (which, as expected, is highest for the
H2 model due to the long process chain from hydrogen production to dispense, and lowest for Plug-in). The sums of these three contributions are displayed in Figure 2.3 as the orange bars.

![Road Transport Sector costs](image)

**FIGURE 2.3** Road transport costs for the ICE (with fuel cost at 0.65 €/l), H2, Plug-in, and BSwap mobility models. ‘Cost of vehicle’ here is not the cost of a new vehicle; it includes the cost of all power items for the vehicle life, including replacement batteries or fuel cells. ‘Energy’ includes the cost of the infrastructures needed to deliver energy to the vehicle.

We note a few points that are not included in these calculations: what value may one attribute to

- The operational convenience of battery swapping versus long times to wait while refuelling, particularly in Plug-in (less so in H2) and heavy vehicles?
- The convenience of enjoying the continuous technology gains for new generations of batteries in BSwap? (As a vehicle ages, its range and power increase, rather than fade.)
- The speed of conversion from ICE to decarbonized mobility, especially for freight and heavy passenger transport, motivated by convenience and cost?
- The decoupling of vehicle and battery lifetime, which translates into economic and materials gains?

All these further favour BSwap relative to the other decarbonized models.

\(^{75}\)Cited times to refuel hydrogen trucks are of the order of 15 minutes.
WHY H2 WILL ALWAYS BE COSTLIER THAN BSWAP OR PLUG-IN

Why hydrogen powered transport is intrinsically more expensive than battery electric solutions.

One may argue about the exact values of the model parameters we used here. However, would other, different but realistic, values, revert the essential conclusion that hydrogen powered transport is more expensive than battery electric solutions? Very unlikely.

There are fundamental reasons for this, and unless they are dramatically changed, the essential conclusion will stand.

Figure 2.4 illustrates this point.

---

**FIGURE 2.4A** Process flow for a battery solution. A nearly reversible process, where a single device, the battery, directly receives, stores and supplies the electric energy.

**FIGURE 2.4B** Hydrogen process chain. The intermediate chemical energy vector, hydrogen, leads to a complex, irreversible, process chain.

**FIGURE 2.4** Simplified representation of battery and hydrogen process chains for road transport.
In the upper part, A, of the figure, we represent the core of the battery solution to mobility. At its heart, lies one single device, the battery, a nearly reversible storage system, with round-trip efficiencies >95% at low charge/discharge rates. A power electronic system (charger) connects it to the electric power supply (e.g. the grid), and another, on-board, feeds the battery energy to the electric motors. The overall grid-to-motor efficiency may be 80-90%.

In part B of the figure, we represent the equivalent flow line for the hydrogen solution, which is far more complex, and includes several irreversible processes. We may identify two core devices, the electrolyser and the fuel cell, but many others are necessary to bring the electric energy from its source to the electric motors using the intermediate chemical vector H2. In this work, the global efficiency was assumed to reach 37% by the 2030’s, and 50% by 2050. (Experts generally agree that these are reachable, but tough, targets to achieve.)

The fundamental reasons why the hydrogen solution is expected to be always more expensive than the battery solutions are therefore:

- Lower efficiency (by a factor of ~2 in the future)
- Higher investment costs (especially for all the infrastructure in the long process chain)
- Higher operational and maintenance costs (both on- and off-board)

**CONCLUSIONS**

Our calculations, within the level playing field as defined, by the reference year, for the four models considered (the incumbent ICE and the three decarbonized electric traction models, H2, Plug-in and BSwap), show that the battery swap model outperforms all others, from the microscopic point of view of a vehicle owner up to the macroscopic point of view of the whole road transport sector.

Adoption of the other models would cause the following estimated increases in global road transport sector costs, as a percentage of Gross National Product, against adoption of the BSwap model:

- ICE (at 0.65 €/l): higher by 0.2% of GNP
- H2: higher by 3.0% of GNP
- Plug-in: higher by 1.0% of GNP

These values are revisited in Chapter IV, when both the road transport and power sectors are considered together.
III • ELECTRIC POWER

The impact of road transport decarbonization in the decarbonized electric system is highly model dependent. BSwap outperforms all others in electric system balance, support, and minimum costs.

When considering the electric solutions to mobility, we must not limit focus to the vehicle itself, or to the road transport sector alone, but instead consider the overall impact of road transport decarbonization on the energy system. The substantial energy consumption by road transport reconfigures the electric system itself: total generation needs, and system costs, must be re-calculated for each of the models, since the system is very differently altered by each of the transport options. As an example, the hydrogen cycle has lower efficiency than batteries; the same transport demand met with hydrogen will therefore require much more additional generation than battery electric vehicles. On the other hand, energy consumption for hydrogen production may be a flexible load to the electric system, much more so than Plug-in battery charging, and the system will also be profoundly affected by this difference.

In this chapter, we therefore analyse how the electric system is differently changed by each of the transport models, with special emphasis first on the technical central issue of balance, and later on costs.

A note on methodology: when calculating the partition of global costs between the two interacting sectors, transport and power, we used a simplified model, that of an average tariff to be paid by the transport sector to the power sector for the electric energy supplied. This tariff is guessed, and a mere instrument to partition costs and benefits to each of the two sectors. This arbitrary assumption is later eliminated: global costs, calculated by taking together both sectors, which is done in Chapter IV, are not affected by this tariff: e.g. too low a tariff just means that part of the costs of transport are simply being transferred to the power sector and vice-versa, the global costs being invariant, independent of the tariff values.

THE IMPACT OF DECARBONIZED MOBILITY IN A DECARBONIZED ELECTRIC POWER SYSTEM

A decarbonized electric power system

The future electric energy matrix is dominated by solar and wind generation
Let us build an electric power system in 2050 for the region we adopted as a model for our study, inspired in Portugal. Our basis is that of the official roadmap for Portugal 2050 \(^{76}\), to which we introduced slight changes only \(^{77}\). The energy matrix of our model is shown in Table 3.1.

<table>
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<tr>
<th></th>
<th>2015 TWh</th>
<th>2050 TWh</th>
</tr>
</thead>
<tbody>
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</tr>
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</tr>
<tr>
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<td>37</td>
</tr>
<tr>
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<td>42</td>
</tr>
<tr>
<td>WtE/Biomass</td>
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<td>7</td>
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<td>0</td>
</tr>
<tr>
<td>Tidal</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**TABLE 3.1** Energy matrices of the reference (2015) and future (2050) models of the electric power system.

We assume that electric energy consumption by 2050 almost duplicates compared to 2015. Half of the increase is due to the general electrification of the economy (e.g. substitution of gas heating for electric heat pumps in buildings), in spite of the expected large gains in efficiency. The other half is due to the electrification of mobility: we assume a future mobility demand (measured at the on-board electric motors) of 20 TWh/year.

On the generation side, hydro power and waste/biomass-to-energy are resource limited; full exploitation of both resources is predicted to add up to only 17 TWh/year by 2050.

On the contrary, wind and solar generation are not resource limited, and their generation capacity can be adjusted via investment: for each model studied, the total wind and solar generation (and therefore their installed capacity, which was taken at a fixed wind-to-solar ratio) was chosen such that the system is always annually balanced:

\[
\text{Total annual generation} = \text{total annual demand} + \text{annual losses}
\]

\(^{76}\) Roadmap Portugal 2050: Ministry for the Environment and the Energy Transition (2019), Roadmap for Carbon Neutrality 2050 (RNC2050). The relative proportions of solar and wind renewable generation were proposed so that cost and yearly seasonal fit are optimized.

\(^{77}\) We decided for a totally decarbonized model power system, contrary to that of the Roadmap, which maintains a residual natural gas generation capacity for grid balance. We agree that maintaining this non-decarbonized capacity is probably a sound choice, as discussed further below, when considering the cost of imbalance. However, in this exercise we opted for this idea of a totally decarbonized grid in order to check clearly the limits of mobility models to attenuate grid imbalance.
The reason for this is the establishment of a level playing field for the comparison of the different mobility models.\textsuperscript{78} Grid losses were taken as a fixed percentage of generation (in modern grids, this varies little, typically from 8 to 10\%). Efficiency losses are more meaningful because they may be strongly model dependent. These losses originate in energy conversion, for instance in water pumping for energy storage in the form of hydric reserve in a dammed reservoir, or in the hydrogen cycle. The total generated electric energy, originating in each of the four resources considered, will always be higher than consumption, of course.

The imbalance problem in the decarbonized electric power system

\textit{Imbalance is the central problem of most decarbonized electric systems} 

Now that we have defined a balanced energy matrix, let us study in more detail the challenges posed by such a system. The central problem is system imbalance, as we demonstrate here.

We analysed all year of 2050 and start by looking first at two weeks of January 2050, which represent a meaningful example, when consumption is high, and coincides with low solar and wind output. (Later on, we extend this analysis to other representative periods of the year.)

Let us then consider demand and generation during these two weeks in January 2050, shown in Figure 3.1.

\textbf{FIGURE 3.1} Demand and generation during two weeks in January 2050. WtE stands for Waste-to-Energy and includes urban and industrial residues and biomass thermo-electric generation.

\textsuperscript{78} The goal of this essay isn’t the fine calibration of the power plants portfolio needed to face extremely unfavorable situations. This study can be done in a second stage, just as the design of many details of the future grid. In this essay we analyze and compare different approaches to decarbonize electric systems using as a reference the Portuguese official scenarios. We try to demonstrate their technical feasibility and their overall cost benefit comparison.
Demand includes general and mobility consumption, both assumed rigid, and with a profile identical to the time series of demand in 2015\textsuperscript{79}, only adjusted to the higher annual consumption by 2050\textsuperscript{80}. There are, of course, many reasons why the demand profile in 2050 will differ significantly from that in 2015 – several of them contradictory\textsuperscript{81}. We didn’t want to become mired in this discussion, which isn’t central to the problems we want to discuss, so this was a possible neutral choice. The most relevant part of this discussion, the total consumption and demand flexibility of mobility, is properly considered within each of the road transport models.

Notice that the demand curve shows several of the expected features: higher daytime consumption, with a strong evening peak, a baseline with an important contribution of industries with large energy consumption and continuous production, a decrease during weekends.

Wind and solar generation, in green and yellow, are the most important, and display their characteristic variability. In winter, solar generation occurs in narrow peaks in mid-day time, which vary according to cloud cover: around hour 255 of this period, the strong winds coincide with a poor solar production. Wind displays its typical variability, with large fluctuations from day to day. We note a tendency for wind to peak at night, which is a good feature for future grid balance\textsuperscript{82}.

Hydro power is displayed here as that which corresponds to the affluence of water into the dams where turbines are located. This is the hydro “raw” generation, simply reflecting the resource, water flowing in the rivers. Below, we shall see how this resource is managed to balance the system: water will be retained in the reservoirs when there is plenty of generation power, and turbined as much as possible in times of need. Later, we shall add water pumping as a means of energy storage, which will further boost hydro power capabilities. Total hydropower installed capacity was taken as 8.5 GW, as assumed in the Portuguese long-term plans.

The thermo-electric generation using waste and biomass as resource is displayed as a constant line: again, this is its “raw” generation, with a power equal to the annual average of the resource. This constant generation power is 0.765 GW, coherent with the total output in the energy matrix. Later, we shall allow the power output to adjust to the electric system needs, treating it as a thermoelectric resource capable of swinging from a minimum output of 0.15 GW to a maximum of 1.5 GW\textsuperscript{83}.

In Figure 3.2 we display again demand, and total “raw” generation, the sum of all four components. Before we discuss this in detail, two notes on the curves displayed. In order to be quantitatively comparable (despite the difference between generation and final demand due to grid and process losses,

\textsuperscript{79} Because hydro generation is a very variable and key component of the electric power system, 2015 was chosen as the recent dry year with a rainfall closest to the predictions of an average year by 2050. All other generation profiles are those for Portugal 2015, adjusted for the future installed capacity. Wind and solar capacities were always adjusted to those necessary for annual generation to exactly satisfy annual demand.

\textsuperscript{80} Demand includes general and mobility consumption (as in the energy matrix), both taken as rigid. Annual general demand was set at 70 TWh, and mobility demand at 24 TWh, higher than final mobility demand in the matrix, as a guessed attempt to compensate minimum losses in the energy transfer from the grid to the electric traction motors.

\textsuperscript{81} The present profile is the result of many different demand activity profiles (from heavy continuous production industry to commerce, services and homes) modified by tariff incentives, presently to encourage night consumption and discourage day and evening consumption. If we look into the future, we can easily guess many possible changes. One example of contradictory trends: because of solar generation, tariff incentives will encourage daytime consumption; but the electrification of transport, with battery charging at times when vehicles are not in use, would favour night consumption.

\textsuperscript{82} Notice this change of perspective: presently, wind production at night is frequently mentioned (probably unfairly) as a disadvantage. The rise of solar generation will change this completely.

\textsuperscript{83} Perhaps an optimistic assumption for the swing amplitude and for the rate of change of power output. Residue and biomass thermal plants prefer to vary output as little as possible, with installed capacity close to the annual average power, for lower costs.
as discussed above), we made a subtle change to what we call Demand and Generation in the next graphs and discussions, so that they are directly comparable:

1. Generation was stripped from its grid losses, which were taken as a fixed percentage of 8%: it is just 8% lower than real generation needs.

2. Demand is not Final Demand (that measured at customers counters, or at traction electric motors of vehicles), it is re-defined to include all power that is taken from the electric system: it includes e.g. the power supplied to pumps for water storage, or to electrolysers for hydrogen production, or to the chargers of batteries for electric vehicles, and therefore includes the inefficiency losses of such processes.

Now in an electric system electric energy cannot be stored \(^\text{84}\), and so there must be instantaneous balance of generation and demand. With these definitions, the generation and demand curves must coincide at all times.

Just by considering Figure 3.2, it is easy to guess that balancing this system is no easy task! Just imagine how difficult it would be to procure the missing power during the evening peaks, of the order of 12 GW, higher than the total system annual average generation power.

It is obvious that the total power availability during this period isn’t enough to satisfy average demand, particularly in the first week. In fact, this is the worst week of the whole year in energy deficit:

- the weather is cold, days are short, and consumption is well above average
- The wind is blowing weakly, rivers are flowing, but not particularly full, and the sun in January, even in days of clear skies, shines at a low angle and for a few hours only.

Interestingly, even in days of such low power availability, the solar peak is often visible above demand: for a few hours in most days, generation is above demand. This also happens in hours of strong wind, as seen on Thursday in the second week.

How can the system be balanced? One obvious solution: import a lot of power across the border, via an interconnection to neighbour countries, during times of need, and export power from the system (or curtail generation) during the excess peaks. Other solutions may be the addition of subsystems with capacity to absorb or inject power as needed. For instance, imagine a hydrogen generation plant, capable of using excess energy for water electrolysis, and of using stored hydrogen gas for injection of extra power in the system when needed. Or a pool heating system that may postpone consumption until hours of plenty and avoid times of power deficit. More generally, balance can be achieved by any storage system, or any generation or consumption systems that are flexible, meaning that they can adjust generation or consumption to the needs of the system.

We shall introduce below into our model system several subsystems with relevant balancing capability and study their impact on imbalance.

\(^{84}\) As such, in any meaningful quantities. It can be stored as water in reservoirs, as chemical energy in batteries or as hydrogen, for instance, but not as electricity.
First, let us recognize that the relevant function to study is therefore the difference between demand and generation, which we shall call the imbalance function,

\[ \text{Imbalance}(t) = \text{Demand}(t) - \text{Generation}(t) \]

\( \text{Imb}(t) \) must be forced to approximate zero: when the system is perfectly balanced, \( \text{Imb}(t) = 0 \), and this is an absolute requirement in any electric system. Departures from zero must be always compensated; for instance, think of cross-border import/export as the way to null imbalance at all times. The imbalance function can then be seen as the power (positive or negative) that must be imported into the system in order to balance it; it is the power-deficit function.

A positive value of the imbalance function means that the system needs extra power, and this is the dominant feature throughout these two winter weeks. Notice that the largest positive peaks frequently occur in the evening, when the sun sets, and demand is maximum (when people come home from work and switch on home appliances).

A negative value of imbalance means that the system has excess power generation, and this occurs mostly during the solar peak hours in these two weeks, but also at times of strong wind generation in the second week.

The function displayed in Figure 3.3 is the Raw Imbalance, that which reflects the resources, with no effort introduced yet to try to balance the system. It is very useful as the starting point, as a quantitative assessment of what needs to be done, and when.
Let us now introduce successive means of balancing the system, and quantify their attenuation effect in the imbalance function, so that we have a clear idea of their real effectiveness as system balance solutions.

Since the system has a high installed hydroelectric capacity (presently already over 7 GW, and 8.5 GW expected by 2050, the time of our analysis), surely retaining the water in the reservoirs during times of excess, and letting it go through the turbines to produce electric power when needed, will have a large effect in system balance. In this study, we used all small dams and run-of-river power stations (within their limited capabilities) to work alongside the large reservoirs for the same aim, balance the system. Also, the waste/biomass-to-energy (WtE) thermal power plants can reduce or increase power output according to needs, and this will also contribute to make the imbalance function plunge towards zero, as desired. The result of putting to work both hydro and WtE to try to balance the system is shown in Figure 3.4, with the curve labelled Dams.

One cannot but question the result: how come, such a large capacity available, for such a meagre gain?

The point is that it is not a meagre gain: the maxima and the minima in the imbalance function are reduced by some 1 to 2GW, a sizeable fraction of the average power. True, this is small compared to the total existing hydropower capacity, but simply there isn’t enough water in the rivers to use all the capacity. The resource for WtE energy is also limited, as is its power capacity (for economic reasons:

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*We used actual data (present annual time series) on these run-of-river contributions to estimate their response in the future system, based on how they presently already vary generation according to system needs. It is not a large contribution, but far from negligible in short time scales of the order of one day. (Part of this response in run-of-river hydro stations originates in the varying turbine flow from upstream larger dammed reservoirs. The downstream cascade of run-of-river hydropower stations responds, with some time lag, to the output of the larger reservoirs.)
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energy becomes much more expensive if a thermal plant is used much below its nominal capacity).

Two weeks in January 2050: Demand and imbalance (raw and attenuated)

FIGURE 3.4 Demand and imbalance during two weeks in January 2050. The blue line, labeled Dams, quantifies the improvement in the imbalance function due to hydropower and WT/E system management.

This result underlines the essence of the problem: the dominance of solar and wind generation produces such huge imbalance that very powerful means must be used to balance the system. When natural gas power stations satisfied a large fraction of electric energy (as in 2021), it was relatively easy to balance the system. Now, in 2050, in a decarbonized electric system, as we stated in the Introduction, the essential problem is no more the cost (economic, environmental) of generation, it is the cost of electric system balance.

We have not used all the “classical” means of system balancing yet: in Portugal, we have been building pumping systems that take water from lower into higher reservoirs, so that this water may later be used in times of need. The total pumping power capacity used in this study is 3.4 GW\(^{86}\), and when we allow all this pumped water storage the results are shown in Figure 3.5\(^{87}\).

As expected, excess energy is mopped up by pumps, except on the Sunday of the first week, when negative imbalance reaches 8 GW, exceeding pumping capacity. The other, most important, and perhaps not so obvious, consequence is that positive imbalance is also strongly attenuated, in fact by a value that exceeds that of water affluence management and waste-to-energy combined: pumps build extra reserves of water, which can be used by the installed capacity in dams when needed. In fact, if we compare the two blue curves in Figure 3.5, we easily conclude that there may be more water going

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\(^{86}\) The value that was used in the simulations in this work for the power consumption in total pumping systems is 3.4 GW. However, new pumping capacity is being installed and planned: by end of 2022 this value is already 3.6 GW, and we foresee that by 2050 it might reach as much as 4.4 GW.

\(^{87}\) Calculations were performed with a combination of our own software with EnergyPLAN, a well-known simple but powerful software developed originally by Aalborg University, in Denmark, with inputs from many researchers since 1999.
up and down the rivers than their natural flow.

Note that the demand curve in Figure 3.5 is not anymore the real demand function: we should add to this rigid function the demand of the pumps. In fact, according to our definition, demand is all the power that is taken from the electric system, and pumps do consume electric energy obtained from the system, even if later on some of this energy is given back to the system (82% of it, due to the round-trip efficiency of pumped storage, in the form of additional hydro generation at later times). We decided to keep the old rigid demand curve in this and subsequent graphs, but it should be regarded as a simple guide to the eye, for easy referral to previous figures. This is further discussed in Annex 8, where the demand function including these flexible components is displayed for the first of these January 2050 weeks.

The investment in new dams with pumping capacity, and in pumps in older dams, was strongly criticized by many in Portugal, on the grounds that the net energy produced by such large investments was minuscule. Our results defy the controversy: dams mainly dedicated to pumping storage are not built for energy production, but rather for system balance, and they are shown to deliver a substantial improvement to the imbalance function. Their main aim is to address the central problem of future electric systems, balance, not energy generation. They illustrate why system balance is expensive: all the investment in pumped storage is dedicated to mitigating imbalance.

Though better than in the raw case, the imbalance function is far from tamed: it is still very far from zero. If we were to balance it, after all large-scale classical means of balancing are used to the limit (all but import/export), as represented in Figure 3.5, we would still need to import energy from neighbours, in the evening peaks of imbalance, with a required cross-border interconnection capacity of 8 GW, about 80% the annual average power consumption. As a guide to the eye, the dashed horizontal

![Graph: Demand and imbalance during two weeks in January 2050](image-url)
Why we need battery swapping for the future energy and transport systems

lines in the Figure represent practically available cross-border interconnection capacity today, some 2,5 GW. Of course, we could invest a lot of money in reinforcing the interconnection capacity and solve the problem of imbalance in these January weeks. However, the problem is bigger than just the need for a huge investment in cross-border new capacity, as we discuss presently.

When we are forced to import a lot of energy, mainly in the evening peaks, through high power interconnections, to satisfy demand and avoid system collapse, are our neighbours likely to be in a condition of excess power in their systems, and therefore happy to sell us that energy at a low cost? Unfortunately, no: the sun sets and demand peaks at about the same time, for neighbour countries. (Wind has a higher geographical variation, but wind conditions are still highly correlated in neighbouring regions). In similar neighbouring systems, also with much wind and solar generation, their problem is most probably the same as ours: a desperate need for power. Of course, somewhere in the world some systems will be willing to sell their excess energy, but how far will they be? The consequence is that, even if our system does manage to buy the energy it needs, it will cost us a very high price.

This is the reason why we must search for the best ways to solve most of imbalance at home, instead of dimensioning cross-border capacity to satisfy all this forced energy import out of necessity to keep the system stable. Interconnection capacity couples systems, and allows international energy trade, which should result in win-win situations. But expensive cross-border overcapacity, not justified by trade, will be a waste of capital.

Let us then look for ways to mitigate the imbalance problem domestically.

Until now, we have considered demand as rigid, and all the effort to balance the system came from generation and pumped water storage. There is, however, another possibility, which might be the key to the lowest costs: turn a substantial part of demand into a flexible load. In other words, what if, instead of insisting on trying to modify generation to meet demand, some substantial part of the demand could be made flexible, and adapt to generation?

We first note that domestic and industrial demand have some capacity to adjust to availability (e.g., management of heating/cooling systems), but very limited, very insufficient for system balance. Which sectors with a substantial consumption could then be made flexible?

One of them is the production of green hydrogen by electrolysis. Electrolysers could function at full power in times of power availability and reduce or even shut down in case of deficit. Additionally, stored hydrogen could be used in fuel cells (or gas turbines) to re-inject power in the system when needed, supporting it as a firm power reserve. However, it is still not clear how large will be the penetration, in the economy, of the hydrogen technologies (which suffer from high costs and low efficiencies), and therefore the fraction of demand that hydrogen generation will represent: if it will remain limited to present volume production, its fraction of demand would be insignificant; if, on the contrary, hydrogen becomes an energy vector with an impact similar to that of natural gas, then this fraction would be substantial.

There is, however, another sector whose impact is much safer to estimate: the obvious large-scale candidate to fulfil this role is mobility. Presently, energy consumption by road transport is 135% that of electricity, and it must be urgently decarbonized. Electric vehicles carry energy on-board, to be

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88 It isn’t just a matter of distance, but also of competition: countries in between will want to keep that available energy for themselves.

89 We might reach that condition, if all plans of the EU for cross-border new capacity are executed.
used when needed; but the time when this energy was taken from the electric system into the batteries is not the time of use (except in the case of trains, or trolley buses), so there is no pre-determination of when mobility fetches its share of energy from the system. How and when energy is taken from the electric system is highly dependent on mobility model, and the consequences of each model will be discussed below in detail.

Here, in order to check the extent to which mobility demand may help solve the imbalance problem, let us jump immediately to the results of a BSwap (Battery Swap) mobility model, which is the most successful in this respect of those we studied. The results are displayed as the reddish line in Figure 3.6.

This result seems almost miraculous, and the conclusion obvious: the imbalance problem in our electric system can be solved by proper choice of the mobility model, namely, by a BSwap model.

FIGURE 3.6 Demand and imbalance during two weeks in January 2050. The reddish line quantifies the improvement in the imbalance function due to introduction of the Battery Swap mobility model BSwap+, essentially solving the imbalance problem. Notice how the imbalance function becomes, at all times, much lower than present cross-border interconnection capacity, represented by the dashed horizontal lines.

Before we study more deeply the reasons for this result, and how different mobility models affect the electric system imbalance, let us briefly consider what happens in a time of excess power in the system, the opposite case of that considered so far. What will the imbalance problem look like in two weeks in May, when the sun is shining and the wind is blowing, generating more energy than necessary to meet demand?

Figure 3.7 shows the demand and generation functions during these two weeks. Note

- the much higher and wider solar peaks, compared to those in January,
- the favourable stronger wind, again frequently peaking at night, and
- the lower demand, due to spring temperatures, averaging 10 GW.
In Figure 3.8 we note how total generation far exceeds demand, peaking at almost 30 GW, and resulting in an imbalance function generally negative, as shown in Figure 3.9, peaking at -18 GW.

**FIGURE 3.7** Demand and generation during two weeks in May 2050.

**FIGURE 3.8** Demand and total generation during two weeks in May 2050. (Note the change of vertical scale.)
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FIGURE 3.9 Demand and raw imbalance during two weeks in May 2050.

Figure 3.10 shows how the progressive introduction of system balancing technologies improves the imbalance function.

FIGURE 3.10 Demand and imbalance during two weeks in May 2050. Note how imbalance is reduced as one progressively introduces system balancing technologies.
These are the two extreme weeks of the year as far as excess power generation is concerned, and even with all classical means available mobilized for system balance (model “Pumps”), the imbalance function still peaks at -14 GW excess power generation. However, even in these extreme conditions, the battery swap mobility model BSwap+ essentially solves the imbalance problem, bringing the imbalance function to very manageable values.

Now that we are confident that mobility may have such a positive effect, let us look more deeply into the origin of this success. The first questions we want an answer to:

- In the BSwap mobility model, how do demand flexibility and bidirectional storage compare? Which is dominant for the success of the displayed model?
- What is the role of each balancing technology in this final successful result?
- How do the other mobility models compare with BSwap regarding their impact on electric system balance?
- How sensitive is balance to changes in residence time of the batteries in BSwap swap stations?

We answer the first question now.

**Which is dominant for the BSwap model success: demand flexibility or bidirectional storage?**

*Demand flexibility is dominant in solving the technical problem of imbalance. Bidirectionality provides further economic advantages, and supply security.*

Let us try to answer this first question by considering in more detail the evolution of the imbalance function during the first of the two weeks in January 2050.

![A week in January 2050: Demand and imbalance](image)

**FIGURE 3.11A** Demand and imbalance in a week of Jan 2050. Note how imbalance is reduced as system balancing technologies are progressively introduced but is still very high after introduction of all classical balance tools available, including water pumping storage.
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A week in January 2050: Demand and imbalance - the effect of flexibility only

FIGURE 3.11B  Demand and imbalance in a week of Jan 2050. Note how imbalance substantially improves with a BSwap mobility model: the lowest lying line (dark blue) is that for a Battery Swap model with no battery-to-grid bidirectionality. Conclusion: demand flexibility alone essentially solves the imbalance problem.

A week in January 2050: Demand and imbalance - the effect of bidirectionality

FIGURE 3.11C  Demand and imbalance in a week of Jan 2050. Note the result of the introduction of bidirectionality in the Battery Swap model (red line). Imbalance peaks are spread into 24h periods: energy import may be realized away from peak imbalance, at more favourable prices.
Imbalance during the whole year of 2050. Light blue includes all classical means of system balance, including water pumping. Dark blue refers to a BSwap model with flexible demand only; red refers to the same BSwap model with added battery-to-grid bidirectionality. The weeks of 2050 shown in the previous graphs are those with highest yearly imbalance in January and May. Conclusion: both BSwap models essentially solve the imbalance problem in long time series.

In Figure 3.11A we display how \( \text{Imb}(t) \) is attenuated from its “raw” condition until all classical means for balance are used, including water pumping.

In Figure 3.11B we add the result of adding flexibility to mobility demand within the BSwap model, shown as the darker blue line.

In Figure 3.11C, we add the result of allowing battery-to-grid bidirectional energy flow (the red line).

Finally, in Figure 3.11D, we show the results for the imbalance functions in the long time series of a whole year.

The conclusion is crystal clear: the main contribution to system balance is demand flexibility, not bidirectional storage capability. In fact, flexible demand essentially solves the technical imbalance problem: the residual \( \text{Imb}(t) \) represented by the dark blue line is not a problem to the grid already. The system does have to import energy at peak imbalance (coincident with peak consumption, and probably peak price), but the total annual amount to import is only a fraction of 1% of annual electric energy consumption.

When we first saw these results, we were taken by surprise: we had estimated the beneficial effect of flexibility but failed to predict its magnitude. How could the January evening imbalance peaks be so dramatically reduced, if no new generation was added to the system (Figure 3.11B)? The answer came after we studied more closely the data\(^90\): the direct reduction to zero of mobility demand at these hours is a large part of the effect; the rest comes from a little help of thermal generation of waste and biomass, but dominantly from hydropower, which comes into action with

\(^90\) A rearranged, more detailed, representation of the data is given in Annex 8.
higher effect at these times, for two reasons:

1. Because hydropower now retains its availability to concentrate on these needy moments, rather than spreading its capacity over time: most of the time, the flexibility of the mobility load takes away much of the need for spending hydro resources; and, of course,

2. Because there is an increase of the energy uptake at times of excess power, when most excess generation is effectively mopped up by the batteries in the BSwap model, instead of wasted or sold at low prices. This increased uptake of excess generation results in a corresponding decrease of energy deficit in times of positive imbalance, which reduces the need to use water resources at these times.

Bidirectionality, represented by the red line, simply allows the imbalance peaks to spread over 24h periods (the period chosen in this calculation model). The technical relevance of this is small 91, but its economic impact is large. What the red line tells us is that there is plenty of extra capacity in the grid-connected batteries to choose the time of import: instead of importing at peak consumption, probably at a very high price, we can shift import to the hours of lower consumption, or, more exactly, to the hours of minimum price. Also, providing firm back-up power for system security has a high value, of course.

We do not show here the detailed result for the weeks in May 2050, with large excess generation, but it is visible in Figure 3.11D: they are the weeks of the year with strongest negative peaks. The conclusion is similar, only applied for export rather than import: flexibility of demand solves the technical problem, but forces export at times of negative peak imbalance, and naturally low price. Bidirectionality allows to choose the best hours to offer excess energy to neighbours, at higher prices, and with much lower requirement of cross-border interconnection power capacity (and therefore much lower investment costs; energy export can be modulated over much longer times, and lower power, than the short, high-power, bursts of excess generation peaks).

Figure 3.11D clearly shows how the best imbalance that could be achieved by all “classical” means, including water pumping storage, displayed in light blue, is still untamed, and how even the BSwap Flex model, with no bidirectionality, solves the problem:

- On the negative part of the imbalance functions, notice how the excess generation 92 is almost totally absorbed by the grid-connected batteries in BSwap, even at the low maximum charge rate of 0.2C (5 hour nominal time to charge, one order of magnitude lower than usual fast charging in Plug-in) allowed in the BSwap Flex model (dark blue). The remaining negative peaks represent only a fraction of 1% of consumption and is practically all within the already existing cross-border export capacity. The BSwap+ model (dark red) introduces a mild 0.1C bidirectional charge/discharge rate 93, and so, with its higher maximum charging rate of 0.3C, shows an even higher capacity of reduction of the negative peaks of the imbalance function.

- On the positive side of the imbalance functions, notice how the need for emergency extra generation or energy import, to avoid grid black-out, simply disappears. The remaining peaks

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91 When we consider only the mitigation of system balance at normal times, as we have been considering in these previous pages. Its technical value becomes high when we consider e.g. the relevance of firm back-up power for system security.

92 Which would inevitably lead to massive curtailment, or to sale at almost zero prices, or to require a heavy investment in high-cost transmission line capacities for long-distance export.

93 Applicable to only a half of the connected batteries (those that are least affected by shallow cycling) and limited to a 10 hour nominal discharge rate (0.1C) and to depths-of-discharge that result in negligeable battery lifetime degradation.
in early January are within import capacity, and even more so in the BSwap+ model. No need for forced import of large quantities of energy at very high prices.

**What is the role of each balancing technology?**

Let us now analyse in greater detail how the different generation and demand technologies contribute to the final result for imbalance. First, note that each of the several curves shown in Figures 3.11 is obtained from running a particular, different, simulation model: we cannot just conclude that the contribution of, say, water pumping, is the difference between the curves labelled “Dams” and “Pumps”, because the whole electric system response totally readjusts for each model.

We therefore propose to lead the reader to an understanding of the contributions of each technology for the final “BSwap” labelled curves, by looking in detail at only a couple of significant points.

**System behaviour at a time of high positive raw imbalance**

We first consider the worst case of positive imbalance in the whole year, the top of the evening peak of the third day of the January 2050 week shown in Figures 3.11 above.

Demand is 16.2 GW, but imbalance comes down to only 0.9 GW with model BSwap+, just at a time when the two major generation technologies fail: the peak happens after sunset, so solar generation is zero, and wind generation is at a very low value of only 0.4 GW, as displayed in Figure 3.1. How is this possible? Which are the most relevant contributions to such a good result for the imbalance function?

One of the most relevant contributions is hidden within “Demand”. Its value of 16.2 GW is the sum of general demand, always considered rigid, of 12.2 GW, and mobility demand, which was also assumed as rigid in the global rigid demand definition, and amounts to 4.0 GW at this point. Now when we adopt the BSwap model for mobility, its mobility demand becomes flexible, so we must subtract this rigid component, and add the new true, flexible, mobility demand, which, at this time of high generation deficit, was naturally zero: no battery charging occurs during the time of this positive imbalance peak. The flexibility of mobility demand is therefore responsible for a contribution of 4.0 GW to the attenuation of imbalance at this point in time, simply by coming down to zero.

These effects may be seen in Figure A8.1, where both (i) the new mobility demand (orange line), which is now flexible, and (ii) the new, deformed, demand curve (continuous black line), which is the sum of the general component of rigid demand (equal to total rigid demand minus its rigid mobility demand component) plus the flexible mobility demand, are displayed.

This is also shown here, in Figure 3.11E, as a cascade of all the contributions at the peak time, the very first of which is the stripping of the rigid e-mobility demand component from the original, totally rigid, demand value, as mentioned just above.
The following contributions, from the usually dominant generation resources, wind (very weak, at 0.4 GW) and solar (it is zero, after the sunset), are at this time almost irrelevant. WtE/Biomass is trying to compensate by generating at full capacity, 1.5 GW.

The highest contribution comes from hydro generation, at 7.5 GW, close to the total power installed capacity of 8.5 GW. It is natural that the system demands such as effort to the hydropower stations, as this is one of the highest imbalance times of the year.

In our modelled 2050 system, as allowed by the EnergyPLAN software we used for these simulations, the total hydro generation is the sum of two separate components. The first is the contribution of all run-of-river and all small hydropower installations, which have limited storage capacity, and therefore limited power generation flexibility, although far from negligible for intraday imbalance compensation; at this point in time, this contribution was modelled at 2.2 GW.

The second contribution is due to the hydroelectric power generation capacity installed at large reservoirs, many of them with water pumping capacity from lower reservoirs that help replenish stored capacity. This second contribution was modelled at 5.3 GW at this time.

We wish to call the reader’s attention to the crucial role of hydropower in the future of the

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**FIGURE 3.11E** Demand and generation contributions to the imbalance at the highest demand point of the evening peak of the third day of the week of January 2050 displayed in Figures 3.11 A to C. Note the major contributions of hydro generation (-7.5 GW) and e-mobility flexibility (-4.0 GW); the final low value of imbalance (0.9 GW) is due to the battery-to-grid contribution (2.0 GW).

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94 This was calculated outside the EnergyPLAN software, which does not allow such flexibility.

95 In EnergyPLAN, all hydropower generation and pumping capacities from large reservoirs are lumped together, and act as a single, very large, hydro installation. This is a serious simplification which limits, of course, adhesion to the reality of the true system. When refining the model electric system, one must go down to this detail, and an outcome of higher model precision may well be suggestions of changes to the hydropower system, e.g. to add pumping capacity, even of low power, to a few more reservoirs of relevant dimension (or eco-sensitive). This could help to maintain a high water level, and so keep reserve storage energy, and maintain environment quality and water reserve for non-energy purposes.

However, for this first approach, when our interest is focussed in orders of magnitude issues of system behaviour, EnergyPLAN is widely accepted as a useful tool.
Portuguese electric system. It is already very relevant presently, but its importance will be much higher in the decarbonized future. That is why pumping capacity is actively being built in Portugal, not only in new hydro resources (which are presently mostly opting for the new generation of reversible turbines) but also being added to older, large, existing dammed reservoirs, thus greatly improving their function from pure generation to generation plus storage. Their main function in the future will be storage, not net flow generation (as underlined by the present choice of reversible turbines). In fact, as mentioned above, net hydro generation from these large reservoirs will be small, compared to the total output of their generators from recycled water (water that is being cycled up-and-down). This effect will be further enhanced by the expected decrease of precipitation, and, perhaps even more importantly, by the future of water management: an ever-increasing fraction of water resources will be diverted to agriculture, industry, human and urban consumption, and ecological ends. We foresee that net hydro generation will play an ever-decreasing role compared to the hydro energy storage role. It is therefore crucial that hydro capacity be properly planned and used, if we are to achieve our decarbonization goals with a stable grid and lowest costs. The hydro generation from large dammed reservoirs mentioned above at that needy time, of 5.3 GW, would not be possible using just the natural water affluence. It is only possible due to the contribution of water pumping and of the indirect effect of flexibilization of the mobility demand reached with the BSwap model.

The final low value of imbalance (0.9 GW) was reached with an exceptionally high contribution of battery-to-grid of 2.0 GW, which is allowed by the BSwap+ model. This order of magnitude of B2G power, in our simulation, happens in only a very few days in the whole year; it is allowed by our BSwap+ model because it is still much below the allowed maximum power, which is limited by the maximum discharge rate of 0.1C of only half of the grid-connected batteries in BSSs. This low-power discharge of 0.1C (equivalent to a rate of discharge corresponding to 10 hours for total nominal discharge) limits B2G power to 3.7 GW for batteries in BSSs with an average 24h residence time, which is almost double the 2.0 GW used here.

In conclusion, the most relevant balancing technologies present at this positive imbalance peak are:

- Hydropower, at a near maximum power of 7.5 GW,
- BSwap e-mobility demand flexibility, which reduces demand from the rigid model by 4.0 GW, and
- BSwap+ battery-to-grid at 2.0 GW, which, taken together with the previous contribution, raises the total balancing power of e-mobility to 6.0 GW equivalent generation, also close to a practical maximum.

**System behaviour at a time of high negative raw imbalance**

Let us now consider a second point in time when raw imbalance is strongly negative. We chose the top of the very last negative peak of imbalance (at peak solar generation) of the Sunday of the same week of January 2050 considered above. The results are displayed in Figure 3.11F.
FIGURE 3.11F  Demand and generation contributions to the imbalance at the highest excess generation point of the solar peak of Sunday in the week of January 2050 displayed in Figures 3.11 A to C. Note the minor contributions of wind (-3.0 GW), WtE/Biomass (-0.15 GW), and hydro generation (-2.1 GW). The dominant contributions are solar (-15.1 GW) and flexible e-mobility demand (+11.9 GW); the final low value of imbalance (0.3 GW) is raised from the lower value of 0.1 GW with no B2G by the battery-to-grid contribution (+0.2 GW).

Total rigid demand is 11.4 GW, to which we first subtract the mobility demand considered as rigid, which is 2.8 GW, then wind (3.0 GW), then solar (15.1 GW), which brings imbalance to a strong negative value. But we still must subtract the generation from WtE/Biomass, which is wisely working at the minimum modelled capacity, 0.15 GW, then hydro at a low 2.1 GW: by now, the excess power (negative imbalance) reaches 11.8 GW.

However, flexible BSS battery charging, at 11.9 GW, puts final imbalance at the very low value of 0.13 GW, which is actually raised by a reverse battery-to-grid contribution of 0.17 GW, raising the imbalance to +0.3 GW. This isn’t strange at all: the system needs this low power energy import during long hours so that it later has the resources to satisfy the higher evening imbalance peak.

The most relevant technologies present at this point are:

- Solar generation, at a power of 15.1 GW, well below the solar maximum, but quite sufficient to be the main cause of a strong negative imbalance peak, and
- BSwap e-mobility flexible demand, which, at a power of 11.9 GW (well below its maximum absorption power), more than totally absorbs the negative imbalance peak.

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*Hydro pumping could also help improve balance; however, in this particular week, of generally high power deficit, satisfaction of the priority needs of mobility use all available extra generation capacity, and pumping never occurs. Pumping happens very frequently, but in other weeks of abundant generation, once mobility demand is satisfied.*
Power capacities of hydropower and of BSSs

Hydro power can swing between the limits set by future modelled installed capacity, namely between -3.4 GW (maximum power pumping capacity\(^{97}\)) and +8.5 GW (total installed hydro generation capacity), as shown in Figure 3.11G. However, the hydropower system should be reassessed, with consideration of minor investments that would improve its performance. This reassessment should also be aimed at preventing the repetition of what happened in recent years in Portugal, namely a depletion of large reservoirs in dry years that led to very low water levels for long periods. Water in dammed reservoirs is an invaluable resource both for energy supply security and for other uses, and this stored capacity should be managed in such a way that levels are kept within acceptable high limits. For instance, in large, dammed reservoirs that presently have no pumping facilities, their replenishment could be considered, e.g. by low power pumps, fed if necessary by imported energy at the lowest prices along dilated periods of time.

These limits of power swing are not so well defined for BSSs.

The nominal power absorption capacity of the batteries resident in BSSs (within the model of an average residence time of 24h) is of the order of 100 GW, a value so high that the power electronics capacity to use it fully will never be installed. In our more practical BSwap model, we limited battery charging rate to only 0.2C (unidirectional model) or 0.3C (with battery-to-grid added), much lower than their nominal power, and, even more practically, we limited the total power connection of BSSs to the grid to 20 GW. This is not a recommended value; it is just a tentative capacity, which will be better adjusted when more is known as the BSwap model is further refined\(^{98}\) and, later, tested on the field. In the one-year long time series referred to above, this limit was never reached: the maximum power observed for battery charging was 15.4 GW, occurring during Spring, at times of high total generation.

A similar lack of determinants is found on the BSSs battery-to-grid generation capacity. It was just model restricted to discharge rates of 0.1C for only a half of the resident batteries (those in a state of charge such that they are least affected by cycling), which results in a maximum generation capacity of 3.7 GW. In practice, during the one-year time series, the maximum value observed for battery-to-grid (B2G) power was 2.0 GW, well below the limit. (These values might be different within the perhaps more realistic BSwap model of unidirectional charging of all EV batteries, the B2G capacity being totally provided by second-life batteries, for which the same restrictions are not imposed.)

On the other hand, when comparing the balancing effects of e-mobility within a BSwap model versus other models, we should consider not just the real B2G generation output capacity of BSSs but also their “equivalent” power generation capacity, as we demonstrated above: when comparing a BSwap model to another, with rigid or less flexible mobility demand, flexibility alone is responsible for a very relevant equivalent balancing power generation, simply by reducing total demand by a large fraction in times of energy deficiency. This equivalent generation, when comparing BSwap to a model with rigid e-mobility demand, was seen to top at about 4.0 GW.

We may state then that BSSs may swing their equivalent power output from -20 GW to +7.7 GW.

These values are displayed in Figure 3.11G.

\(^{97}\)This maximum power capacity used in our model is already being reinforced, and might become perhaps 30% higher by 2050, if we take into account all existing plans plus possible addition or upgrade in dammed reservoirs.

\(^{98}\)For instance, by considering different regional needs within the national electric system. Local BSS grid connection capacities may be designed for local stability above that necessary just for the national system.
Why is this power capacity range important? Let us stress this point by looking at the imbalance problem from a different angle:

Assume an electric system that is annually balanced, in other words, total annual generation exactly meets total annual demand. Then the area under the positive part of the imbalance function is exactly equal to the area of its negative part.

Now assume that, in this system,

- an important enough fraction of demand becomes flexible enough, and has enough power capacity to absorb all excess generation peaks of negative imbalance. Then the positive part of imbalance must reduce to zero as well, and the system will be precisely balanced.

BSwap e-mobility demand nearly satisfies the first and last assumptions, and its flexibility is ample, but limited by the residence time of the batteries in BSSs. It therefore provides a valuable contribution to system balance but cannot reach perfect balance on its own. However, hydropower has just the longer times response (especially due to storage in the large reservoirs) that lack in BSSs, while it lacks the power to absorb the negative imbalance peaks (limited by pumping power capacity): together, BSwap e-mobility and hydropower can achieve nearly perfect balance, no other resources being necessary.

Another limitation of the balancing capacity of these systems is, of course, energy: how much energy can be used in a flexible way in the hydropower system and in BSSs?

The total net energy produced by hydropower is modelled as about 10 TWh/year, or about 10% of total generation, but this doesn’t answer the question of energy availability for system balance.

In run-of-river and small dams, the energy available for flexible use is a small fraction of the total. It was estimated from the present observed response to present electric system balance intraday needs, and then re-calculated for the needs of the future system of Portugal 2050. The result is a modest, but
not negligible, flexibility of generation. (We argue that this is a lower bound of capacity, since we only used present observed flexibility, not its real limits.) This was an expedite but obviously limited way to estimate this flexible energy generation capacity; model refinement, again going down to detail, would also be welcome.

Large reservoirs have, of course, a higher capacity, and can be used for much longer response times, even at the seasonal scale. Their total useable capacity will amount roughly to some 5 TWh, or about only 5% of total annual generation, therefore corresponding to about two and a half weeks of consumption. However, the definition of “useable” capacity is bound to be reviewed, taking into account the future of water management, as mentioned above.

Consider now the unidirectional BSwap model. Total energy consumption by battery charging is about 24 TWh/year, or about 25% of all consumption (13 weeks of annual total consumption), and this does tell us something about energy availability for system balance, because all this energy is flexible consumption, just limited in the time scale. The average energy taken from the electric system for battery charging at BSSs is about 64 GWh/day. In a BSwap unidirectional model with an average residence time of the batteries in BSSs of 24h, this energy is totally flexible, within the limitation of 24h use. From the system balance point of view, this flexible load of 64 GWh is roughly equivalent to a constant load plus a battery with storage capacity of about 58 GWh, which represents 5.4 hours of total average consumption. (In the 48h BSwap model, the average daily use of energy is the same, but BSSs have double resident capacity, and furthermore are allowed to take the required energy from the system with lag times of the order of a week, instead of just one day, thus significantly further improving balance capability beyond the intra-daily limit.) Note that all this balancing capacity comes for free to the electric system, it is paid for by mobility.

In our limited bidirectional BSwap model, an equivalent storage of 10 GWh/day would be added for a 24h model, and double this in the 48h model. (If, in the future, bidirectionality is rather guaranteed by second-life batteries alone, these capacities might be different, and differently time-limited, but it is too early for a quantitative estimate.)

These estimations confirm the high relevance of flexible e-mobility consumption to system balance, even with its time range limits, and how system balance capability is further enhanced by bidirectionality.

Conclusions

We could look closely at other interesting points in time, to confirm how the electric system, armed with the BSwap model of road transport, reacts in all sorts of different situations occurring during long time series. However, we think that these two examples above are sufficient for the reader to

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100 Other aspects are important to look at, e.g. the varying state of replenishment of the dammed water reservoirs or the state of charge of the batteries in BSSs (the two sites where energy is stored and used with flexibility, apart from also the storage of waste and biomass ready for electric power generation use), but these are technical details better treated in shorter, technically focussed publications.

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99 A flexible 24h load of total energy E may be roughly modelled as
- a rigid constant load, adding up to energy E in 24 hours, plus
- a variable load with zero net total energy, with energy just being transferred up-and-down according to system needs, the equivalent of battery-to-grid and grid-to-battery: a battery equivalent (with 100% efficiency).

The capacity of this equivalent battery depends on E=64 GWh and on the maximum power of the BSSs connections to the grid. If the full 20 GW considered here is used in this calculation, then the result is 58 GWh equivalent battery capacity. Note that if we were to install such a battery capacity for dedicated energy storage, the cost of just the batteries (excluding all power systems, ...), at their low cost of 70 €/kWh, would mean an investment of 4 060 M €, or an annualized investment cost over 650 M €/year, which, with the BSwap model, comes for free to the electric system because it is paid for by transport.
reach the level of deep understanding of the interactions of the different mechanisms at play in such an electric system.

The main take-away from this study is how the interplay of the two major flexible generation and flexible consumption systems,

- hydropower (armed its intrinsic flexible generation, together with pumping facilities, which are flexible demand), and
- battery charging stations (armed with their intrinsic demand flexibility and added battery-to-grid flexible generation),

is responsible for the excellent results on the electric system balance.

Note that no further storage is needed. This is a strong statement, which goes against present estimations by energy experts in Portugal. These two powerful systems are quite sufficient to handle all the vagaries of demand and the even more stringent vagaries of a generation system highly dominated by wind and sun, two resources that by 2050 might well be responsible for over 85% of electric generation\(^{101}\).

The conclusion is that the good results of the BSwap model on electric system balance are no miracle, they are soundly based on the interplay of flexible demand and generation of e-mobility and hydropower. This leaves a few serious questions for the design of future energy systems:

- Yes, we need short-term storage, but much less than usually assumed. The flexible demand of e-mobility takes away most of the need for short-term storage, with its equivalent battery capacity up to 58 GWh; and the bidirectional capacity of BSSs offers a further 10 GWh of battery capacity. Add the hydro storage system, with its short-term and long-term capacities, and we probably have already all the storage we might need\(^{102}\).
- We do need long-term storage; but how much? In the Portuguese example, we have demonstrated that with the current plans\(^{103}\) hydropower is on the way to meet all that is needed: no further investment in storage (be it hydrogen, compressed air, batteries, or any other technology) may be necessary\(^{104}\) (at least definitely not at the scale presently expected to be necessary). Hydropower may become the all-dominant large-scale storage that we may need for security of supply.
- Yes, we need cross-border interconnections, but how powerful? The results above show that

\(^{101}\) Solar and wind, in our models, were responsible for about 84% of total generation. This percentage could be higher if (i) less biomass is burned, or (ii) internal consumption grows more than modelled (e.g. due to an even higher electrification of the economy) or (iii) the system becomes a net exporter, as many propose. Also, a much higher percentage is obtained if we were to adopt the H2 model: its low efficiency must be compensated by a lot more new solar and wind generation.

\(^{102}\) We are not ruling out the use of additional storage for local application, e.g. to increase stability in a micro-grid. However, even in such cases the need might be rather less than anticipated: note that the distributed characteristic of the 2 000 BSSs offers local storage capacity that may be used in many such cases. Another common foreseen use of much storage capacity is in solar and wind parks, to absorb peak generation and shift energy injection in the grid to more convenient periods, and, together with curtailment, contributing to grid stabilization. This is being imposed by regulation, with the consequence that cost per unit energy injected in the grid by solar and wind generation units becomes higher than if all generated output were simply injected in the grid (due to the added costs of these storage and management systems, and efficiency losses). Again, such dedicated storage might be substituted with advantage by resorting to local BSSs at a far lower cost (with connection via dedicated direct power lines, or via regular distribution-grid lines). BSSs would easily absorb peak generation and provide grid stability; and the result would be cheaper electricity prices.

\(^{103}\) Preferably including the results of a reassessment, which might suggest a mild increase of pumping capacity, in new and existing large dams, as mentioned above.

\(^{104}\) Beyond what is being done and the small investments resulting from the suggested reassessment of the hydro system.
electric system balance and stability may be mostly found inside borders, at least in the case of the Portuguese system. Interconnection needs for short-term balance are much less than usually assumed, and for seasonal balance the needed power capacity should also be reviewed, because all overcapacity that is not essential for security, or paid for by commercial trade, is a waste of capital.

The impact of different mobility models in the decarbonized electric power system

*Mobility may help solve the imbalance problem of the electric system, but different models differ widely in their impacts.*

The main aim of this section is to calculate how each of the mobility models considered, H2, Plug-in and BSwap, alter the system imbalance.

As a preliminary note, we point out that the model Pumps includes all energy demand in 2050, about 94 TWh/year\(^1\), as a rigid function; in other words, it assumes an electric mobility system with a rigid demand, which added to all other demand, results in the demand and imbalance functions displayed above.

The attenuation of this imbalance function within the different mobility models will be mainly due to two reasons:

1. Demand flexibility
   Trains must have electric energy delivered as needed when travelling; the demand profile of trains is perfectly rigid, not adaptable at all to imbalance in the grid, and the same is true for trolley buses and trucks.
   The opposite is true for hydrogen powered mobility: electrolysis of water may produce hydrogen mostly in times of abundant power and avoid hours of power scarcity; hydrogen is then stored and dispensed at any time into the on-board high pressure fuel containers of trucks and buses, which then use this stored energy when travelling, as needed. There is a complete decoupling of electric energy demand from the system and energy demand at the wheels, and this will be reflected as a strong attenuation of the imbalance function within model H2. The limits to this attenuation are economical: because hydrogen technology is expensive, the installed capacity will probably be limited to that which may work with a capacity factor above, say, 2500 hours per year\(^2\), and therefore in practice frequently incapable of absorbing the excess generation peaks (which furthermore are rather higher in H2 than in the other models, due to the low efficiency of the hydrogen cycle, which implies a need for much extra wind and solar generation, with the consequent increase of imbalance).

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\(^1\)The final general consumption is taken as 70 TWh, which, added to the final e-mobility consumption at 20 TWh, would justify a total demand of 90 TWh. However, our definition of demand includes all energy that is taken from the system (except ohmic grid losses), and so it must include the inefficiency losses of both (i) the storage cycle by water pumping and (ii) the losses grid-to-motor to satisfy final e-mobility demand. The 94 TWh value is adjusted to the actual values of pumped water (an iteration process for each simulation) and assumes the best possible efficiency of the process to bring energy from the grid to electric motors in EVs (this component is refined later, within each of the e-mobility models).

\(^2\)Below this capacity factor, the investment costs will weigh more heavily, making hydrogen more expensive. The number mentioned, 2500 hours, is not a barrier, of course, it is just a frequently cited number in the literature as a reasonable limit to low-cost hydrogen production. Now the hours of excess power in our electric system are less than 2500 hours/year, so the absorption of the generation excess is necessarily limited by economics: electrolyser stacks will work below this capacity factor, and so the investment costs will loom high on hydrogen cost.
With Plug-in, the on-board batteries store energy, which is used while travelling as needed. Is Plug-in demand then as flexible as that of H2? No, because EVs charge by plugging directly to the grid. We clarify the issue with two examples:

1. In long distance travel, when an EV stops for re-fuelling, it needs the energy at that moment, it cannot wait for a time when the system has excess power. It is rigid, or dumb, demand.

2. On the contrary, if an EV is charged at home, or in smart public slow chargers, some degree of intelligent charging is possible, taking advantage of times of lower tariffs.

With Plug-in we may therefore expect some attenuation of imbalance, but not much. The main reason is that in Plug-in battery charging is not decoupled from vehicle use.

How can energy demand from the grid by battery EVs be entirely decoupled from vehicle use?

We said it before: by using battery swapping, rather than plugging the on-board vehicle battery directly to the grid. Batteries will be grid connected for long times in swap stations, and charge only at the most favourable times for the grid. A large balancing effect is expected.

2. Power-to-grid

A plug-in EV may give some of the energy in its on-board batteries back to the grid in times of need, with a bidirectional connection. This process is called Vehicle-to-Grid, or V2G. It sounds like a great idea, until you work out the details: battery degradation, constraints of vehicle use, and cost, make V2G a technology of limited relevance for grid balance (see Footnote 45). It is included in our Plug-in model, but constrained to a sensible magnitude, resulting in modest balance gains.

The conclusion is quite different in BSwap: the large resident capacity in swap stations, the ability to choose which batteries are in a state of charge that makes them virtually immune to degradation for shallow cycling, and to respond promptly and directly to the requests of the grid operator, make this technology profitable for the swap station owner, and to the grid. There is, of course, another asset that can be used in swap stations: second life batteries. Because swap stations are responsible for battery quality assurance, many batteries will be taken out of circulation yearly at BSSs and classified as (i) fit for second life (not good enough for EVs, but healthy enough to be used for grid support) or (ii) to be recycled (end of useful life). Now all the electrical power circuits and connection to the grid exists already in the stations, so it is most probable that medium and large station owners will include grid services using these second-life batteries. We chose, however, not to include this in our present BSwap model.

In H2, it is possible to use stored hydrogen to inject energy back into the grid – but not using the on-board fuel cells. This power-to-grid technology is therefore outside the mobility model used here, in which we account for the hydrogen generation necessary for road transport only. We discuss this round-trip (electric energy to hydrogen, and back to electric energy) balance via

107 For present Li-ion batteries, 50 000 cycles of 5% depth may be possible with little observed degradation when the state of charge is low, say 10 to 50%, and at low rates of charge/discharge. Under these conditions, battery degradation is negligible.

108 We foresee that, in practice, second-life batteries as BSSs will probably account for all bidirectionality and diminish the residence time of EV batteries in BSSs for the same balancing effect. This lowers the total number of batteries needed, simplifies power systems management, and reduces costs. However, we chose not to include second-life batteries in the models studied here, because of uncertainties in their availability (the fraction of healthy second-life batteries is still unknown): all results here on imbalance and costs assume no second-life battery use. We decided, for the time being, not to risk including in our models results that would rely on them, although we are convinced that in a real future world, second-life batteries will most certainly be used in BSSs, with the consequence of further decreasing global costs and improving system performance.
hydrogen later, when discussing the cost of system imbalance (or, more precisely, the cost of balancing the system).

In this discussion of the impact of mobility models in the decarbonized electric system of 2050, we chose models for mobility that differ somewhat from those used in the previous chapter, which were set at an intermediate time, and were radical in assuming all road transport was of a pure type, H2, Plug-in, or BSwap. We therefore need to adjust the definitions for this study.

**Definitions of the mobility models interacting with the electric system in 2050:**

1. **H2**
   The main differences from the H2 model as defined above are
   - The round-trip efficiency of the hydrogen cycle is assumed higher, reaching 50% by 2050 (perhaps optimistically);
   - Only heavy vehicles run on hydrogen. Most experts in the field assume hydrogen fuel cell light vehicles will never be competitive with battery powered light vehicles, and we accompany them here: we assume light vehicles will be battery powered, and charged by plug-in, within the present variant of the H2 model studied here. Light vehicles are allowed constrained V2G; heavy vehicles, running on hydrogen, have no bidirectional connection to the grid. Total consumption of heavy vehicles from the electric system, for the hydrogen cycle, was therefore about 20 TWh/year (twice that for the consumption at the on-board electric motors of heavy vehicles of ≈10 TWh/year, and also almost twice the demand of battery heavy vehicles).

2. **Plug-in**
   Vehicles were sorted out into 5 classes (light passenger, light shared, and light duty; and busses and heavy freight trucks), each with different characteristics, such as energy consumption, profile of use, percentage of dumb charging (fast or slow), of intelligent unidirectional charging, and of V2G. Their interaction with the electric system was iteratively calculated.
   Among other important data, charging efficiency was set from 90% for slow charging down to 75% for ultra-fast charging, and the efficiency of each class of vehicles was obtained according to their estimated fraction of fast charging.

3. **BSwap**
   To understand better the role of demand flexibility and of battery-to-grid, three models were built, two with no bidirectionality and increasing battery residence times at swap stations, and the final one including battery-to-grid:
   a) **Model BSwap Flex 24h**
      Batteries have an average residence time in swap stations of 24h, and no battery-to-grid facility. Total nominal battery connected capacity is 68 GWh (about 10% of battery capacity on wheels). Charging rate is limited to 0.2C (0.2 kW per kWh of battery capacity). “Flex” in the model name underlines the fact that battery charging is a flexible load, with no

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109 A more detailed definition and calculation procedures can be found in the scientific paper cited before, Why we need battery swapping technology, A.M.Vallera, F.M.Nunes, and M.C.Brito, Energy Policy 157, October 2021, 112481, [https://doi.org/10.1016/j.enpol.2021.112481](https://doi.org/10.1016/j.enpol.2021.112481). The calculations used the EnergyPLAN software.

110 Iterations were needed because each class of vehicles deforms the imbalance function differently, so their adaptation to imbalance and the final necessary generation had to be obtained this way.
b) Model BSwap Flex 48h

Batteries have an average residence time in swap stations of 48h, with 75% of them being swapped within 24h, and also no battery-to-grid. Total nominal battery connected capacity is 137 GWh (about 20% of battery capacity on wheels). Charging rate is limited to 0.2C. (This is the model that produced the results represented as the dark blue lines in Figures 3.11.)

c) Model BSwap+

The final one, named BSwap+ or simply BSwap, the same as in b. above, with an added bidirectional component limited to a rate of 0.1C, applicable only to half of the connected batteries (those in a state of charge that are least affected by cycling) and with depths-of-discharge that result in negligible battery lifetime degradation\(^{111}\) (the model corresponding to the reddish lines in Figures 3.11 and 3.12).

The charging energy efficiency (no fast charging, only slow charging, mostly at constant rate, at optimum charger efficiency regime) justifies the assumed 87% round-trip efficiency used in the BSwap model.

In all models, the demand flexibility and the power-to-grid possibilities were used to minimize the imbalance function differences to zero\(^{112}\).

In order to guarantee a level playing field, generation was adjusted to demand so that the system was annually balanced. The annual sum of the imbalance function is then zero (the annual energy imported is exactly compensated by exported energy). This has to be achieved iteratively, as changes in the generation capacity of solar and wind cause e.g. different storage pumping patterns, and if, for instance, total annual pumping consumption increases, total annual demand also increases (due to the pumping cycle inefficiency) and must be compensated by further solar and wind generation (always maintaining their relative proportion).

Results: the imbalance function for Plug-in, H2, and BSwap models

Figures 3.12 shows the imbalance functions that result within each of the mobility models in three different 2-week periods of the year.

In Figure 3.12A, we display the imbalance functions for the same two weeks in January 2050 considered before, which include the period of the extreme positive imbalance sequence of the year (worst period of the year of insufficient generation to meet demand).

Note how the imbalance function of model “Pumps”, which assumes a rigid demand for road transport, is attenuated with the Plug-in model for road transport, then further attenuated by H2, and much more so by BSwap.

This same pattern of decreasing imbalance is observable in Figure 3.12B, which displays the results for the extreme weeks of negative imbalance (excess generation capacity) of May 2050, and in Figure 3.12C, which displays the results for two rather more peaceful weeks in August 2050, representative of

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\(^{111}\) As already mentioned above, these characteristics might well be altered using second-life batteries in BSSs. We would expect similar outcomes on system balance, but with no need for bidirectional cycling of batteries for EVs, and a lesser number of extra resident batteries in BSSs.

\(^{112}\) We limited the outcome to this technical aim of minimizing imbalance. The alternative of building a financial model, which would have to include regulations, markets, etc., would make the results less universal, more dependent on idiosyncrasies and more complicated to interpret. Imbalance, on the other hand, retains the essential basis of system economical differences.
Two weeks in January 2050: Imbalance with Plug-in, H2 and BSwap

FIGURE 3.12A  Imbalance during two weeks in January 2050. Note the different attenuations of the imbalance function for each of the mobility models Plug-in, H2, and BSwap.

Two weeks in May 2050: Imbalance with Plug-in, H2 and BSwap

FIGURE 3.12B  Imbalance during two weeks in May 2050 for each of the mobility models Plug-in, H2, and BSwap.
As discussed above, Plug-in allows only a moderate attenuation of imbalance, of the order of ≈ 1GW on average in imbalance peaks.

The H2 model allows a more substantial attenuation of imbalance, say an average of ≈ 3GW in imbalance peaks. It is limited because (a) it was applied only to heavy transport (half the total road transport energy), (b) it requires additional solar and wind generation (due to its low efficiency, and the consequent higher fraction of variable generation increases imbalance), (c) the model assumes a limit to electrolyser power due to economic considerations, and (d) it assumes absence of bidirectionality (energy flows only from the electric system to electrolysers to trucks and busses, there is no vehicle-to-grid energy transfer). Despite its substantial attenuation, the imbalance function of this H2 model still shows positive peaks of 6 GW, and negative peaks exceeding -12 GW.

We note that a H2 model with increased electrolyser power and bidirectional coupling with the electric system would be able to reproduce the excellent results of BSwap, because in H2 there is also complete decoupling of road transport demand and energy taken from, and injected into, the electric system. The limitations are economical, rather than technical.

The imbalance problem is essentially solved with the BSwap+ model. Even in the extreme weeks, the power deficit or in excess is always below 2,5 GW, the assumed cross-border interconnection capacity, and most time of the year the imbalance function is very close to zero, as seen in the two weeks of August.

The reasons for this success are (a) the flexibility of road transport demand, completely decoupled from vehicle use, (b) the high power of grid-connected batteries, while resident in swap stations, even with the imposed limitations of slow charging, which makes them capable of absorbing virtually all excess generation in the system, and (c) their simple use as bidirectional storage devices, even with
stringent limitations used to limit battery degradation to negligible values which we imposed in the model: on power, on depth of discharge, and on selection of which batteries may be used for battery-to-grid support.

Note that this high balancing capacity comes very cheaply to the electric system: the most expensive components are the batteries, then the chargers, and they are paid for by mobility. BSwap adds, to the electric system,

- an equivalent storage capacity of the order of 58 GWh, with an equivalent power capacity ranging from -20 GW to +4 GW, coming for free from the unidirectional component: it is all paid for by road transport (within the BSwap Flex 24h model); and
- a further storage capacity of 10 GWh with a bidirectional power capacity of 3.7 GW, coming from the bidirectional component of BSSs, which comes at a low cost, that of power B2G electronics (the only component not paid for by road transport).

One consequence of this is that electric energy for general consumers will be cheaper.

Let us now try to answer the fourth relevant question asked above:

**How sensitive are BSwap models to changes in residence time of batteries in swap stations?**

As expected, the results on imbalance improve with longer residence times. A 24h residence time is sufficient for essentially solving the imbalance problem, but significant improvements are obtained with 48h average residence time and with introduction of bidirectionality.

To answer this question, we show the results for the three different Battery Swap models defined above, BSwap Flex 24h, BSwap Flex 48h, and BSwap+.

**FIGURE 3.13A** Imbalance during two weeks in January 2050: a study on the effect of residence time and bidirectionality in BSwap models. “Flex” variants are purely unidirectional, while BSwap uses battery-to-grid bidirectionality. Pumps and H2 are also displayed, as references.
The results are shown in Figures 3.13A, B and C, which display the imbalance functions during two weeks in January, May and August 2050 resulting from the different models. The imbalance functions of the Pumps and H2 models are also displayed, as references.

**FIGURE 3.13B** Imbalance during two weeks in May 2050: the effect of residence time and bidirectionality in BSwap models.

**FIGURE 3.13C** Imbalance during two weeks in August 2050: the effect of residence time and bidirectionality in BSwap models.
A few points:

a) All these BSwap models greatly improve system balance, and all essentially solve the central problem of the future electric system, imbalance.

b) As expected, the results improve with longer residence times, and with the introduction of bidirectionality. (They would also improve if the limitation of the slow charge at a rate of 0.2C were relaxed to a higher value.)

c) All BSwap models fare better than H2.

Global quantitative indicators of electric system balance quality

We define three numerical indicators that globally characterize system imbalance for year-long periods within each model, so they can be compared in a quantitative basis. BSwap outperforms all other models.

To compare quantitatively the global results of each model, we define three quality indicators:

1. **IE** = Forced energy trade
   This is the sum of the positive part of the imbalance function in a whole year, which can be interpreted as how much energy the system is forced to import \(^{113}\) to be balanced at all times. It is therefore an indicator of how imbalanced the system is, energy wise. Note that our model electric systems are always assumed to be energy balanced on an annual basis: annually, generation exactly satisfies total consumption. IE is therefore designed to characterize deviations from balance, be they seasonal or intra-daily. It is expressed as a percentage of total electric energy consumption.

2. **IP** = Power imbalance
   Consider two systems with the same IE, one of them requiring this energy along seasonal periods, spread in time, at low power; the other requires the same total energy, but in shorter, higher power, bursts. Although both are forced to import the same total energy, the first one requires a cross-border interconnection (or back-up power at home) of low power capacity, working for long hours per year, while the second requires high-power capacity, active in shorter periods. IP is designed to distinguish these situations and is defined as the power capacity of a cross-border interconnection (or firm power backup) needed to satisfy all energy import needs to the 99th percentile of total energy consumption \(^{114}\). (We found this definition to provide a more stable indicator than just the maximum power needed for 100% satisfaction of energy import, which may be distorted by freak, very short, events, that may occur in a few hours per year only.) It is expressed as a percentage of the average electric power consumption.

3. **IG** = Additional generation, needed to compensate losses due to energy conversion inefficiencies
   The energy that must be generated to satisfy demand depends on system efficiency. IG is a measure of system inefficiency and is defined as the extra energy that must be generated to

\(^{113}\) This energy in default can of course be obtained by other means rather than import (e.g. by firm generation power back-up at home) but “import” is a simple, clear, concept. It is also equal to the sum of the negative part of the imbalance function, the excess energy that must be exported (or curtailed, ...), because in our calculations we always forced yearly balance: total energy imported = total energy exported.

\(^{114}\) In other words, the tops of the peaks that lie outside IP correspond to leaving unsatisfied only 1% of consumption. This choice has the advantage of eliminating from the global indicator IP infrequent extreme peaks, with low statistical significance, so that IP has a more robust character as a system indicator.
compensate system inefficiencies and so balance the system. It is expressed as a percentage of total electric energy consumption.

Note that lower values of the indicators correspond to higher quality of the system balance. They were calculated for the following models:

a) Raw: no balancing tools used, imbalance = (rigid demand) - (raw generation resources). Demand includes that of mobility, assumed rigid, besides general (also rigid) demand.
b) Dams: Hydropower (without pumping) and waste/biomass-to-energy are active to attenuate the raw imbalance.
c) Pumps: hydro storage with pumping is added.
d) E-mob: electric mobility is allowed to become flexible, its flexibility calculated within each e-mobility model:
   d.1 Plug-in: all vehicles are battery electric, charged by plugging vehicles to a grid-connected socket. Some demand flexibility and V2G are accounted for.
   d.2 H2: all heavy vehicles run on hydrogen, the others are Plug-in.
   d.3 BSwap 24h: Previously named BSwap Flex 24h. Battery swap model with 24h battery residence time in BSSs, and no battery-to-grid.
   d.4 BSwap 48h: Previously named BSwap Flex 48h. Battery swap model with 48h battery residence time in BSSs, and no battery-to-grid.
   d.5 BSwap+: Same as d.4, with bidirectionality, Battery-to-Grid (B2G), added: (48h + B2G). Also referred to simply as BSwap.

The imbalance functions for all these six c. and d. models are the ones illustrated in Figures 3.12 and 3.13 above.

These global indicators quantify “negative” system quality: the model providing the lowest numerical values is the best. Their numerical results for each model are shown in Table 3.2, and in Figures 3.14 to 3.16.

<table>
<thead>
<tr>
<th>Road Transport models</th>
<th>IE Forced energy Trade</th>
<th>IP Power imbalance</th>
<th>IG Additional Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid mobility demand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw</td>
<td>23 %</td>
<td>97 %</td>
<td>3 %</td>
</tr>
<tr>
<td>Dams</td>
<td>18 %</td>
<td>80 %</td>
<td>3 %</td>
</tr>
<tr>
<td>Pumps</td>
<td>9 %</td>
<td>50 %</td>
<td>5 %</td>
</tr>
<tr>
<td>Flexibilized demand according to e-mobility model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plug-in</td>
<td>7 %</td>
<td>40 %</td>
<td>5 %</td>
</tr>
<tr>
<td>H2 (Heavy v. only)</td>
<td>5 %</td>
<td>25 %</td>
<td>14 %</td>
</tr>
<tr>
<td>BSwap 24h</td>
<td>2 %</td>
<td>5 %</td>
<td>3 %</td>
</tr>
<tr>
<td>BSwap 48h</td>
<td>1 %</td>
<td>0 %</td>
<td>3 %</td>
</tr>
<tr>
<td>BSwap+ (48h+B2G)</td>
<td>1 %</td>
<td>0 %</td>
<td>3 %</td>
</tr>
</tbody>
</table>

**TABLE 3.2** Global system indicators for each of the models.

The importance of a low IE may be understood with the following reasoning:

As stated above, energy trade between connected systems, taking advantage of differences in market prices on both sides, is of course generally virtuous. However, forced energy trade, between
highly correlated systems, is ruinous:

- forced energy import occurs most frequently at peak consumption, in the evening of both countries; and
- forced export is most frequent at the solar peaks, which are simultaneous in both countries as well.

Note that a similar high cost of imbalance mitigation occurs if one tries to satisfy these imbalance peaks by keeping sufficient back-up generation power, which will be idle most of the time.

BSwap models outperform all other e-mobility models (Table 3.2 and Figure 3.14): the residual IE of 2% (2.5 times less than for H2, 3.5 times less than Plug-in) for the more modest BSwap 24h plunges down to 0.86% for both BSwap 48h models; in the case of BSwap+, its B2G capability eliminates expensive forced trade altogether: the residual 0.86% can be imported or exported at times away from imbalance peaks.

Let us perform a quick estimation of the costs involved. If we assume that the average difference between buy and sell prices in these circumstances is of the order of, say, 100 €/MWh, then the difference in cost to the system, between Plug-in and BSwap models, due to forced trade alone, would be ≈630 M €/year, or ≈14% of the total cost of electric energy generation, or 0.3% of GNP. The price of electricity could be diminished by this much if the BSwap+ model were adopted, from this effect alone.

FIGURE 3.14 | Forced cross-border energy trade (IE) as a percentage of total final demand (90 TWh/year in our model system) decreases from the Raw condition as more balancing technologies are added to the system. Note the very different balancing capability of the different e-mobility models: (i) Plug-in (gray), (ii) H2 (green), and (iii) the 3 Battery Swap models tested (orange). The visible orange dot with the dashed line refers to BSwap 24h, while the two BSwap 48h, with and without battery-to-grid, are indistinguishable in this scale, both represented by the dot at the lowest point of the continuous orange line.
IP measures the power capacity of cross-border interconnections (or of back-up power capacity) needed to approach system balance, and is displayed in Figure 3.15. Note that Plug-in would require a power capacity of 4.1 GW, whereas in BSwap 48h the required power capacity is 0 GW. This means that even if all cross-border interconnections were severed, balance would not be lost. (This is a consequence of IE being lower than 1% for these models.) In other words, cross-border capacity is not necessary for system balance, it is just useful for normal trade activities only. This is the reason why we stated above that the very high investments programmed to increase cross-border capacity in Europe should be revisited in the light of this new approach: how much capacity is really needed for energy trade and security?

**FIGURE 3.15** IP (relative power imbalance) evolution as more balancing technologies are added to the system. IP is defined as the cross-border power capacity sufficient to satisfy imports needed to keep the system 99% balanced energy-wise (1% only of total final consumption remaining unsatisfied) divided by the average consumption power (10.2 GW). Note the very different cross-border interconnection capacity needed for balance for the different e-mobility models: (i) Plug-in (gray), (ii) H2 (green), and (iii) the 3 Battery Swap models tested (orange). The visible orange dot with the dashed line refers to BSwap 24h, while the two BSwap 48h, with and without battery-to-grid, are indistinguishable in this scale, both represented by the dot at 0%, the lowest point of the continuous orange line.

The evolution of IG is shown in Figure 3.16. Note how the introduction of pumped storage increases losses, due to the round-trip efficiency (set at 82%, better than average present, already demonstrated in reversible pumping systems) of the water pumping cycle. Also, BSwap is below Plug-in, mainly because of the lower efficiency of fast charging, unavoidable in Plug-in and totally absent in BSwap. The most significant difference in IG is observed for the H2 model: despite only heavy vehicles being hydrogen powered, and of the round-trip efficiency of the hydrogen cycle being set at 50%, a much higher value than present, the extra generation needed to power the hydrogen model is outstanding.
An extra generation of 9.4 TWh/year\(^{115}\) (10.5% of all electric energy consumption, at an estimated cost over 400 M€/year, or 0.2% of GNP) is necessary to compensate its lower efficiency. A much higher value would result, of course, if all vehicles were considered as hydrogen powered.

\[\text{FIGURE 3.16} \quad \text{IG measures the extra energy generation needed to cover inefficiency losses in the system. The graph displays its evolution as more balancing technologies are added to the system. Note how strongly it varies for the different e-mobility models: (i) Plug-in (gray), (ii) H2 (green, only heavy vehicles powered with hydrogen), and (iii) the 3 Battery Swap models tested (orange, the 3 models studied being almost coincident IG-wise).}\]

\[\text{Other impacts of e-mobility in the electric system}\]

There is a large variety of support services that electric systems must meet in order to deliver reliable high-quality power to their customers. Assume, for instance, that a major generator suddenly fails; how can the electric system survive, avoiding a major black-out? Smaller incidents are more frequent; how capable is the system to ride through smaller disturbances? Many electric appliances – and regulators – require an extremely narrow frequency regulation; this is becoming ever more difficult in modern grids, as the excellent rotational inertia of thermal and hydro-generators is being overridden by ever more wind and solar generation; how capable is the system to perform the required demanding frequency regulation under all circumstances? Several systems are labelled as critical, and power supply must not be interrupted; does the system have firm power back-up, in case of a failure? Once a blackout occurs, does the system have black start capabilities, which help restore supply in a short time? Almost islanded microgrid systems require special support; can it be supplied? System voltage support is becoming more of a problem, particularly due to fast changes in power generation.

\(^{115}\)Recall our definitions within this chapter, namely regarding grid losses, which are not explicitly treated here.
in regions with a high density of solar or wind parks\textsuperscript{116}; can the system maintain power quality? How such support services are qualified and paid for is highly dependent on local energy market regulation. Some designations are quite common, such as that of Primary Control Reserve, which refers to compensation of very short-term fluctuations, from milliseconds to seconds in duration.

Besides these services intended for power quality, one may consider many others of purer economical value. For instance, can a BSS (or a network of BSSs) defer, or entirely avoid, high-cost investments that would otherwise be necessary in the short term for an electric system? Or is it possible to choose the time in import/export, according to price signals, away from imbalance peaks (as discussed above, when introducing bidirectionality into BSwap models)?

The question here is: Will the rise of e-mobility permit such further impacts on the electric system? Which e-mobility models will be likely to supply some of these further valuable benefits to the electric system?

The answer is that the BSwap model, which concentrates a large, grid-connected, battery capacity in its thousands of Battery Swapping Stations, will undoubtfully provide the base for a vast array of services to the electric system, part of which probably with the added resource of second-life batteries.

Why is BSwap superior to H2 in this respect? A few reasons:

- Present batteries have fast response times, down to the millisecond. Fuel cells, on the contrary, ramp up power slowly (\textit{e.g.}, of the order of half a minute for 0 to 50\% of the nominal power, in the extreme case of a cold start).
- Power controllers in battery systems are all solid-state electronics, comparatively cheap and reliable compared to those for fuel cells.
- The major cost of grid-connected battery capacity in BSSs comes cheaply to the electric system, because it is mostly paid for by mobility. On the contrary, there is no practical way to avoid all the cost of dedicated fuel cells and power systems in the H2 model, if one aims at servicing the electric system with bidirectional power flow.
- BSSs, large consumers of an average power of 2.5 GW, may provide services in two ways: by immediate interruption of consumption, and by injection of power in the system, up to their combined grid connection capacity (20 GW assumed here, twice the average national system power, for grid-to-batteries; for batteries-to-grid, while in principle a power up to the 20 GW of the grid connection could be used, in practice a much lower power will be installed, designed as sufficient to meet system needs). Hydrogen generation facilities with grid re-injection capability cannot match the fast response nor the power capacity of BSSs.

It ought to be noted that the H2 model has an advantage over BSwap, on long-term storage for weekly or seasonal grid support: in BSwap available stored energy is short term only, up to days, not months. However, it is debatable whether this hydrogen service will become economically competitive on a national scale, \textit{e.g.} versus (i) hydro reserves, (ii) import/export, or (iii) simply to retain a few gas turbines, the solution proposed by the Portuguese Roadmap 2050: it is an economic solution (the upfront investment has been redeemed already), and to pay for power security with very modest emissions (corresponding to a very few percent of total generation) may be a fair trade-off for the foreseeable decades to come. Another alternative is to convert turbines to use hydrogen instead of

\textsuperscript{116} Think of clouds passing over a solar park, or sudden gusts of wind, which may cause undesirable local disturbances that must be acted upon, \textit{e.g.} by sufficient fast power reserve and reactive energy management.
natural gas, a technology that has been demonstrated; the capital investment should be much lower than to install dedicated fuel cells, and decarbonization would be deeper – although probably more expensive than the natural gas solution.

BSwap will also prove superior to Plug-in, namely because there is no practical way to service the grid from small scale highly dispersed chargers, irregularly connected to vehicle batteries. It is debatable whether even a limited V2G model may succeed, one reason being the size of the necessary investment and the low return. On the contrary, a BSS concentrates about a thousand batteries, and so has the right dimension (say, 70 MWh capacity, and 10MW power grid connection) for grid services. If regulation is appropriate, the further investment for bidirectional grid services by BSSs should be amply justified.

The aim of this section, dedicated to services to the electric system other than system balance at the time scale considered above, is to call the attention to future possibilities that the BSwap model is best positioned to deliver, which need technical study and development, and probably adaptation of regulation.

Such possibilities will undoubtfully unfold within a BSwap model and will have a significant economic impact. However, we do not take this into account when calculating relative costs and benefits of the different models under comparison in this present study. We hope other researchers will quantify them in the future.

Conclusions

The main aim of this sub-chapter was to understand the impact of several models for decarbonized road mobility on a decarbonized electric system. The first important conclusion is that electric system imbalance will be the central issue in many future electric systems, and it must be technically and economically solved.

We defined and explored several models for road transport decarbonization, taking care to build as much a level playing field as possible for the comparison of their impact on the future decarbonized electric system. The focus is always to search for an answer to the choice determining question: which models provide the better solutions for future decarbonized electric systems?

The main conclusion is that the BSwap model outperforms all others from the combined points of view of electric system balance and minimum need for increased energy generation to satisfy mobility demand.

The emphasis in this sub-chapter was on the technical issues; in the next sub-chapter we shall look into economic issues.

ELECTRIC POWER SECTOR COSTS

The electric sector includes all generation, transport and distribution systems that satisfy electric energy demand. It includes the grid and grid connected systems, but also e.g. dedicated power generators that are not grid-connected.

The aim of this sub-chapter is to estimate the difference of total costs of the power sector that results from application of each of the mobility models. Note that for this calculation we revert to the 2030’s interim data, rather than the snapshot at 2050 used in the first part of this chapter, so that
costs are coherent with those obtained in Chapter II for the road transport sector costs. Therefore, the
dvalues used here are not the ones shown in the first part of the Chapter. For instance, just above the
round-trip efficiency of H2 by 2050 was taken as 50%, whereas here we revert to 37% only, the value
for efficiency assumed for the interim 2030's.

In our simplified models, demand is divided into two components, general demand and mobility
demand:

- General demand is considered rigid, with a time series similar to present (just multiplied by a
  factor to account for global increase in electricity demand, in our case from present to 70 TWh).
- Transport demand is the distinguishing component because it is strongly dependent on
  transport model. Final transport demand, measured at on-board vehicle motors, is 20 TWh, the
  same for all models.

Our aim here is to estimate how global sector cost varies with transport model. We focus therefore
on the differences only, and do not aim for precise calculations: here we only want to achieve an
order of magnitude of the most relevant costs that are amenable to reasonable estimate. We start by
analyzing which components of cost are most sensitive to model variations:

a) Cost of Generation
   It includes capital, O&M and other costs to build and run the electric energy generation plants
   that satisfy total yearly demand, including energy losses. This is a relevant item, sensitive to
   the mobility model. And, from our model calculations, we already have data on the needs for
   each model, namely additional wind and solar capacity, and total generation needed to satisfy
   the same final demand.

b) Cost of balancing by “classical” existing 117 means
   If we take the means with balancing capacity that already exist or are planned to exist by the
   time of our calculations (waste/biomass, dams, hydro pumping), the extra energy needed (due
   to losses in, e.g., hydro pumping) is already incorporated in a); and since we are not considering
   here new investments beyond these, this item has low sensitivity to the mobility model, and is
   not further considered for model comparison.

c) Cost of residual imbalance
   Electric system imbalance must be always zero, so the cost of further balancing (after all the
   classical existing means have been used) must be estimated, particularly because it is highly
   model dependent.

d) Grid costs
   These are the costs for the grid (transport and distribution) to handle the power to satisfy total
demand. They are model sensitive: relative to ICE, the added energy to satisfy electric mobility
demand, and the different ways balance is achieved, will result in different solicitations to
the grid 118. For instance, H2 requires an increase of almost 2.5 times the added electric energy

117 We assume as “existing” all the means that are presently installed plus all those that are part of the national plans for the
next decades, namely in waste/biomass, hydropower, and pumped hydropower, coherently with our calculations carried
out for the future system.
118 They include namely additional investments and grid losses.
required by BSwap, and Plug-in extensively uses the low-voltage distribution grid, which H2 and BSwap don’t. The estimation of costs is further complicated by the possible use of local dedicated renewable generation capacity to supply hydrogen production plants or battery swap stations. For Plug-in it is difficult for dedicated capacity to have a high relevance\textsuperscript{19}, contrary to the cases of H2 or BSwap, which in the limit might have hydrogen plants or BSSs mostly grid insulated. (See a short discussion of grid-connected versus dedicated generation in Annex 7.)

In conclusion, grid costs are important, and should be estimated once the details of how each model is implemented are known. As a guess, we expect that BSwap would demonstrate the lowest costs, H2 being penalized by a higher energy consumption and a higher residual imbalance, and Plug-in by its extensive use of the low-voltage distribution grid and highest imbalance correction. However, because of the difficulty of calculation within our models without further assumptions, and therefore loss of generality, we decided not to include explicitly, for now, this item, in the comparative study of electric system costs, except by a penalization of Plug-in relative to H2 and BSwap, in the form of a guessed coefficient affecting the added cost of generation within the Plug-in model.

e) Cost of guarantee of quality of service

This refers \textit{e.g.} to the costs of reserve power, frequency regulation, transient ride-through capability, etc. This is model dependent: data on the electric system balance clearly demonstrates the superiority of the batteries in the BSwap model, and their role in grid support, both as flexible demand and power reserve, for times from the millisecond up to one or a few days\textsuperscript{120}; H2 would come second, Plug-in and ICE last. However, and although it will be a relevant, and model sensitive, cost component, we shall not try to quantify it here.

f) Other costs: commercial, \ldots: we assume they will not be sensitive to mobility models, and thus ignored.

In conclusion: we shall concentrate only on the

a) Cost of Generation, and the

b) Cost of residual imbalance

the ones that are most obviously model dependent and amenable to simple, rough, estimations.

\textbf{The cost of additional generation}

\textit{The unit cost of additional generation in H2 and BSwap is an average cost of solar and wind generation, taken as 45 €/MWh; Plug-in is penalized by a higher unit cost to compensate the higher grid costs, at 64 €/MWh.}

We are interested in discussing differences between models, so what we need is the cost of the additional need for generation in Model A vs Model B. For instance, H2 needs more generation than

\textsuperscript{19} Due to the intermittent nature of power supply by Plug-in chargers to vehicles, and to their geographical distribution. Only in special cases, such as a large parking lot or a logistic hub, dedicated generation might be somewhat relevant.

\textsuperscript{120} On shorter time scales, it is an interesting discussion how the power capacity of resident batteries could be used as Primary and Secondary power reserve, and how it would compare with, \textit{e.g.}, H2 round-trip power plants. Probably frequency regulation via synthetic wave forms will be successfully applied in the case of battery power, since their response can be regulated down to milliseconds, as required by Primary Reserve.
THE TRANSITION
Why we need battery swapping for the future energy and transport systems

BSwap: how much more will it cost to provide the additional total annual energy needed?

Additional generation will probably be obtained by increasing the capacity of solar and wind generation, so we assume its cost is an average of solar and wind generation costs. We could calculate additional costs by using the cost of capital, O&M, ... for the new capacity; however, we chose instead the far simpler assumption of an average cost per additional unit of energy, which we arbitrarily guess as a fixed value of 45 €/MWh.

We therefore decided to use the following costs per additional unit of energy, within each of the electric mobility models:

- H2: \( c_{H2} = 45 \text{ €/MWh} \)
- BSwap: \( c_{BSwap} = 45 \text{ €/MWh} \)
- Plug-in: \( c_{Plug-in} = 64 \text{ €/MWh} \)

A few comments on these values:

1. The value chosen for H2, 45 €/MWh, is arguably close to an average of solar + wind generation cost by the reference year.
2. BSSs are more capable than H2 plants to provide several grid services, as discussed above. It is therefore natural that the net cost for BSSs might be below that for H2. However, because the benefits of such services were not quantitatively estimated, and because we do not want to introduce arbitrary values that might be seen as favouring one model against another, we decided to use the same H2 value for BSwap.
3. The value for Plug-in was arbitrarily guessed, somewhere between the pure generation cost and the retail energy price, taking into account the above considerations on grid costs. It is far below present tariffs paid for the use of chargers, but these include several system costs that are not increased by Plug-in demand, in particular grid balancing costs, which we calculate separately. Also, our Plug-in model assumed some demand flexibility and V2G, which ought to decrease the average cost. Finally, we are really interested in the differences between models rather than absolute values. We are certain other researchers will refine this value in the future; for the moment, it seemed a reasonable guessed compromise that does make energy more expensive in Plug-in due to its use of the grid (especially the low voltage distribution grid) but does not try to include all grid cost components. (See Annex 7 for further discussion.)

Note that these costs are not at all tariffs. Tariffs are a mean to partition costs and benefits among different players and may virtuously try to be based on fair cost compensation. Here we refer to system costs, based on investment and operational costs, irrespective of players, one step above worrying about partition. In this work, we used arbitrary tariffs as a means to partition costs between the transport and power sectors, but their possible bias is eliminated in Chapter IV, when we calculated the global costs for the two coupled sectors, our final aim.

The ratio of solar vs wind capacity is chosen to minimize total cost. For instance, solar might be locally cheaper than wind; however, a pure solar solution might turn out more expensive than a solar + wind solution that would spread generation over longer hours. We used the ratios between solar and wind (on- and off-shore) obtained by the national optimization process within the Roadmap for Portugal 2050.

A further explicit note: In BSwap we allow capacity-factors down to the order of 1500 hours/year, which were estimated from a good charging rate for batteries and enough for grid balance, not by cost, because the power systems for battery charging in BSwap are much less expensive than a H2 plant and are therefore not cost limited. (They are just power electronics, much cheaper than the systems of an electrolyser plant, and furthermore partly paid by mobility. The batteries come for free, entirely paid for by mobility.) This is part of the reason why BSwap is better than H2 in grid balance and other services. (See Annex 8 for a related discussion which clarifies this point further.)
The results of the calculation of the cost of additional generation for each model are shown below in Table 3.3.

**The cost of imbalance**

*We try to estimate the cost of eliminating the residual imbalance, the imbalance that remains after all “classical” means of balancing (including pumped hydro) have been used. After consideration of alternatives, we decide to use a hydrogen round-trip model for this estimation.*

**Energy import/export model**

If the electric system under scrutiny has strong cross-border connections with a much larger system, one obvious way of balancing it is to export energy when in excess and import energy when in need.

Now an interconnection between systems A and B, which is not cheap, is a good investment when there are non-synchronous variations of energy cost in A and B; in other words, when there are differentials in cost such that make it worth for the high-cost side to import energy from the low-cost side, even after payment of a toll fee (due to the installation and operation costs of the interconnection).

The fundamentals of gain for the system A+B, at each exchange of energy E, is represented in Fig. 3.17. High-cost generation in A is shed, causing price to fall to A'; in B, higher demand causes price to increase to B'. If A-B is large, the gain will be more than enough to pay the interconnection operator a “toll” fee. Coupled systems A and B are more efficient than uncoupled systems A and B.

![FIGURE 3.17](image)

The fundamentals of cross-border energy trade: System A, with a high cost of energy, buys energy E from system B rather than producing it. The overall gain is the area of polygon AA'B'BA (minus “toll” fees).

However, there are two problems when applying this to future electric systems, both dominated by wind and solar generation:

1. The marginal cost for solar and wind generation is zero. Cost is mostly determined by the initial
investment, and by operational costs independent of production: the “fuel”, sun or wind, is free. In a renewable energy dominated system, the classical approach for price establishment, which is based on market closure by e.g. gas turbines, fails. This is a problem for market regulation, but here we do not discuss further this fundamental issue.

2. In similar systems, both dominated by wind and solar generation, a high degree of correlation of price in A and B is expected: usually, when A wants to import energy from B, say in the early evening, B is most probably not in an excess energy condition: B is probably wanting to buy energy as well. The same is true of excess energy: at the solar peak of A, say, B will be also on the solar peak (only for systems over 3,000 km distant in the east-west direction would solar peaks be sufficiently displaced for a good fit).

This causes a problem: in times of excess for both A and B, B will buy energy from A (and eventually sell it via cross-border connections to a distant region which is willing to accept the energy) only if A offers it at a very low price. On the contrary, if both A and B are in need for power, B will only sell to A at a very high price, as B itself is trying to import it, possibly from a distant region.

In systems with strong correlation of imbalance (due to similar patterns for generation and consumption), synchronous variations of price will be the rule, causing a large swing in energy prices: very high in times of need, very low in times of excess. The extremes in price would occur at the extremes of imbalance: if, for instance, Imb(t) is very large in A, it means that energy is very scarce in A, as it will be also in B: energy will then be very expensive. The opposite is true for Imb(t) strongly negative: prices will be very low.

Despite these large price swings, the differentials between A and B will remain relatively small, because they will generally be synchronous.

The consequence is that relying on import/export of energy between such correlated systems is not a good means of achieving system balance, since it would be very expensive.

One might resort to considering instead a distant region, where scarcity is not a problem at peak imbalance in the national system being studied. The problem with this solution is that it is long distance import, and a national system will be competing with all its neighbours, so it should again be expensive.

On the contrary, if neighbour countries have very different energy mixes (an example might be Spain/France, another Austria/Germany, as shown in Chapter V), import/export may be generally a good way of helping balance and of generally decreasing costs for the coupled systems.

The conclusion is that the import/export model does not provide a robust and general model for estimating imbalance costs.

We therefore resort to estimating the costs of system balance using internal, not transnational, means, as a sensible and more general (and therefore more comparable) way of estimating imbalance costs.

Note that we are not at all ruling out cross-border energy import/export, which will exist whenever such operations are justified by profit. Cross-border capacity should be sufficient to satisfy

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124 An interesting point here is that frequently it will be cheaper to curtail power at the generation plant than try to sell it at a price that will not compensate the use of the grid and of the interconnections, its net worth becoming perhaps even negative. An extreme case is that of congested power lines, which cannot accept any further traffic.

125 Neighbours with different electric energy matrices may indeed help in achieving balance; however, in most cases, relying totally on import/export to achieve balance would still be far too expensive, and local balancing capacity should be used.
commercial demand, including not only local exchanges between A and B but also, e.g., long distance traffic between A and C, supported by commercial contracts that include the payment of “toll” fees.

What we are saying is that relying on import/export between mostly synchronous systems to balance a national grid would be ruinous, and that the result of estimating imbalance costs for a given country would produce completely different values, depending on the energy matrix of the neighbour we might choose to estimate these costs.

An internal, national, model to estimate the costs of imbalance

In the search for a sensible and general model to estimate the cost of system balance, we finally opt for a hydrogen round-trip model.

We start by considering the simpler case of negative imbalance.
In this case, there is an upper bound for cost, which is that of curtailment. If energy is curtailed, the same amount must be generated, to preserve annual balance. Therefore, the cost of curtailment is just

\[(\text{Cost of curtailment}) = c_0 \times (\text{curtailed energy})\]

where \(c_0\) is the average marginal generation cost, which we took as 45 €/MWh.

Let us consider now positive imbalance.
This is a more difficult problem to solve since power scarcity must be satisfied: extra power must be injected in the grid.
Every country or region will search for its own least cost solutions; it might be to increase storage systems such as hydro pump capacity, or compressed air storage, or batteries; or additional back-up generation (based e.g. on stored fuels, presently a current practice using natural gas, in the future perhaps using a decarbonized fuel), or any other, depending on regional assets. However, this does not give us a general estimate of the cost of imbalance.

One way of solving this problem more generally is to resort to a round-trip hydrogen cycle such as depicted in Figures 3.18 and 3.19: additional back-up generation which uses green hydrogen as the storage fuel. This is attractive for our purpose of estimating a bound to scarce energy cost because it can be set up anywhere, will probably be cost competitive to any other unused large-scale solution, and is amenable to calculation.

We shall therefore explore an H2 round-trip model to estimate the cost of imbalance.

The H2 round-trip model

Energy from times of surplus power in the grid (negative imbalance) is used for electrolysis to produce hydrogen; hydrogen is stored and used at times of power scarcity (positive imbalance) to satisfy the extra demand. The electric system must increase total generation capacity (namely solar and wind) to compensate the losses due to limited round-trip efficiency.

Two important points of the model:

1. We assume a round-trip efficiency of 50% for the hydrogen cycle, higher than that assumed for transport. In this closed loop plant, stationary, with no need for high pressure compression nor distribution, we assume this higher value is attainable already by the reference year.
2. We assume additional generation is satisfied by a multitude of fuel-cell stacks. Some of these will satisfy the bottom of the imbalance function, close to zero, and will enjoy high capacity-ratios of, say, 40%; on the other hand, those that are necessary to satisfy the hours of very high imbalance will be mostly idle, working only during the few hours of the year when negative imbalance peaks. The cost of generation is dominated by the cost of energy for the first stacks, and will be lowest; for the others, cost becomes ever higher, as investment costs loom at low capacity-factors. In order to avoid very high costs for high imbalance peaks, our model puts a cap on cost, justified by the assumption that when costs become high some alternative will become available to supply the needed energy.

**FIGURE 3.18** The hydrogen round-trip model was used for estimating the cost of balancing an electric system. Hydrogen is produced by electrolysis at times of power abundance, stored, and later used to re-inject power in the grid in times of power scarcity.

**FIGURE 3.19** An illustration of the hydrogen round-trip model for system balance, pointing out some of its limitations. Power may be extracted from the grid when the imbalance function is negative, but

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An alternative to fuel cells for gas-to-power are the existing generators powered by natural gas turbines, converted to burning hydrogen instead of natural gas. If this proves viable, it could be an interesting alternative, particularly since much of the investment is already amortized.
limited by available installed electrolyser capacity. Re-injected power is limited by fuel-cell installed capacity, and re-injected energy by round-trip efficiencies of the order of 50%: re-injected energy is only ≈1/2 of that which was taken from the grid.

The consequence is that within our model the cost of energy produced by hydrogen fuel cells and injected into the grid is mostly dominated, in our model for the future reference year, by the cost of energy, not by the cost of investment. The higher efficiency of 50% translates therefore into much lower costs than if we used the transport modelled efficiency for the 2030’s, below 40%.

The results of application of the model to solve the residual imbalance problem to each of the electric systems, calculated for each of the mobility models, is included in Table 3.3.

**The cost of the power sector: comparison of ICE, H2, Plug-in and BSwap models**

*The BSwap model outperforms H2 and Plug-in because it combines excellent demand flexibility with high cycle efficiency.*

The impact of the road transport model on costs of the electric power system, shown in Table 3.3, was estimated using only the contributions of 1) additional generation (with the correction for grid costs in the case of Plug-in) and 2) imbalance, calculated as described above. In the case of H2, two cases were considered: (1) all road transport is by fuel-cell powered vehicles, (2) only heavy vehicles are fuel-cell electric vehicles, all light vehicles are Plug-in.

**Cost of system balance**

The cost of system balance (presented in the second row of Table 3.3 and shown in the form of the orange bars in Figure 3.20) is highest for Plug-in and ICE because of poor (in Plug-in) and non-existent (in ICE) flexibility of electric demand for transport. Even though some flexibility and V2G were introduced in the Plug-in model, the additional generation needed to satisfy electric mobility (via solar and wind additional generation, therefore producing higher raw imbalance) is responsible for the value higher than for ICE, where demand was considered rigid, but with relatively lower solar and wind contributions: the higher the additional generation necessary to satisfy road transport demand, the higher the fraction of non-dispatchable renewables (wind and solar), and the higher the raw imbalance that must be brought to zero.

In the case of H2, the increased additional generation due to the low efficiency of the hydrogen cycle (which significantly increases raw imbalance, because of the higher fraction of wind and solar) is compensated by the very good electric demand flexibility (limited only by economic reasons), the result being a much lower imbalance cost than for Plug-in, despite the larger fraction of wind and solar. (The similar values for H2 for all-hydrogen mobility, or only for heavy vehicles powered by hydrogen, have the same root cause: the all-hydrogen vehicles case needs a higher generation, but is better at balancing than the fraction of Plug-in light vehicles, despite its lower additional generation needs.)
### TABLE 3.3
Comparison of the Power Sector costs estimated within each of the electric mobility models and the incumbent fuel powered transport model. Units are M€/year. The costs of the H2 model were estimated in the cases of all vehicles, or only the heavy ones, running on hydrogen.

BSwap shows the lowest costs for system balance, mostly due to its excellent demand flexibility, with a smaller contribution from its battery-to-grid feature. The high energy efficiency of BSwap also helps, of course, by decreasing the fraction of solar and wind generation necessary to satisfy demand, when compared to H2.

**Cost of additional generation**

The cost of the additional generation (first row of Table 3.3, and the blue bars of Figure 3.20) is lowest for BSwap, because of its high efficiency cycle. Additional generation in Plug-in is only marginally higher than in BSwap, but its cost is penalized by its use of the grid: we assumed a system cost for additional generation of 64€/MWh for Plug-in, and only 45€/MWh for both H2 and BSwap. Despite this low cost for additional generation, H2 is penalized by its low efficiency.

The arbitrarily fixed higher cost of energy for Plug-in relative to H2 and BSwap (64 vs 45 €/MWh) penalizes Plug-in by 436 M€/year. However, we note that even if the difference in cost is set to zero, the global conclusions on the relative costs of each technology would be qualitatively the same, but with Plug-in quantitatively in a somewhat better position than shown here and in the next chapter.

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127 Remember that the economic value brought about by bidirectionality in BSwap, which allows to choose the best times for import/export of energy, higher capacity-factor utilization of cross-border interconnections capacity, and therefore avoidance of high-cost increased capacity of such power lines, was left out of our model calculations, although it should be significant.
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**FIGURE 3.20** Comparison of two significant, model dependent, contributions to the costs of the power sector: (1) the cost of the additional generation necessary to power road transport, and (2) the cost of balancing the electric system. Notice the low cost of balance in the H2 model compared to Plug-in or even ICE (due to demand flexibility of the hydrogen generation plants), but the much higher need for additional generation, due to the low efficiency of the hydrogen cycle. The blue line represents the difference to BSwap of the sum of these two cost contributions for each model.

Figure 3.20 shows the results in the Table for the two cost components and the total difference of these two costs of each model to BSwap. It only represents the power sector cost components; it does not include the income (third row of Table 3.3) due to payments from the transport sector to the power sector.

**Received from mobility**

The third row of Table 3.3, labelled “Received from mobility”, shows the same values, with negative sign, that were displayed in Table 2.4, and represents the flux of money between the two sectors, estimated via the guessed average tariffs, which simply apply a partition of the costs between the two coupled sectors. The negative values found for the total sector costs found in the last three rows of Table 3.3 simply mean that the partition of costs between the power and transport sectors was arbitrarily
set (by the guessed tariffs) as relatively more favourable to the power system; a different choice of the numerical values for tariffs might unbalance the partition the other way. This has, however, little relevance: as we show in the next chapter, global costs of the coupled sectors are independent from these tariffs, and these global costs are the really meaningful final results.

**Conclusion**

In conclusion, regarding the two cost components of electric power sector which were considered, namely the cost of additional generation and the cost of balancing the system, the BSwap model outperforms H2 and Plug-in because it combines excellent demand flexibility with high cycle efficiency.

**The cost of electric energy for general consumers**

*An outcome of the BSwap model is the lowest electric energy cost for general consumers.*

One definite conclusion of these rough, order of magnitude, estimations of costs is that the BSwap model of road transport leads to the lowest cost of electric energy for the general consumer.

Before we review the fundamental reasons for this, we stress that part of the costs estimated above in the first and second lines of Table 3.3 are paid for by mobility, as represented in its third line. How much is paid was estimated by a guessed average tariff, set for instance at 40€/MWh for the H2 and BSwap models, and of 100/150€/MWh for Plug-in (heavy/light vehicles), but this tariff is merely a method for the allotment of costs for each of the two coupled sectors, power and transport. With these tariffs, the cost of electricity with BSwap would be 704 M€/year (0.3% of GNP) lower than with H2 (from the last rows of Table 3.3); however, if we used a lower tariff, such as expected by the H2 industry, say of the order of 20€/MWh only, then the consumers of electric energy would be penalized by a surcharge to the electric system of some 1 864 M€/year (0.9% of GNP).

The negative values for costs of the power sector for Plug-in (and for the H2 model applied for trucks only, the rest of mobility being satisfied by Plug-in) result from the use of the high retail price of energy assumed for Plug-in. In the next Chapter, when we consider together the coupled power and transport systems, we will obtain a clearer view of global costs, with the partition between each of the sectors open to adjustment by market and policy forces, not subjected to these arbitrary guessed average tariffs.

The reasons for the costs of the power system with BSwap being less than those with Plug-in derive from the relative lower system balancing capacity and higher use of the grid (particularly the lower voltage distribution grid) by Plug-in.

Let us now analyse the fundamental reasons why BSwap leads to lower electricity prices than H2.

First, we note that the cost of solar and wind generation is determined by the investment costs (dominant) and the operational costs (lower), fixed and independent of how much energy is actually sold; and that the total revenue from sales must compensate costs (otherwise no capacity would be installed). Therefore, any energy curtailed or sold at near zero price zero means that the rest of the energy must be sold at a higher price to pay for costs.

Now both H2 and BSwap create large scale flexible demand for “excess” power, which raises its value. However, BSwap is superior to H2, and some of the reasons are explained here below.

1. The power that can be installed in a H2 plant is limited: below, say, 2500h/year the cost of hydrogen starts being dominated by the investment and operational costs, not by the cost of energy. For
a contained cost of hydrogen, the installed power capacity is constrained by the economics of hydrogen. Note that this is true in any case, be the source of energy dedicated generation, the grid, or a hybrid solution. This is an especially serious issue in the utilization of generation excess for hydrogen production, because the hours of negative imbalance are usually below 2500 hours/year. With such low capacity factors, installed electrolyser capacity must be limited, and curtailment (or export at very low prices) of a significant fraction of excess generation is unavoidable.

2. In BSwap consumption, such constraints are much milder: transport pays for the batteries (the most expensive item), which, as seen above, have a huge nominal power capacity, more than necessary to soak up any excess peaks; and battery charger power electronics is cheap, particularly when mass produced with standards (both investment and maintenance costs are low), and also paid for by transport. Therefore, installed power capacity is constrained only by how much is really needed by the electric system for lowest cost. Note that battery charging at BSSs at a 0.2C rate corresponds to capacity factors down to 5 hours/day (a good fit to absorb the solar generation peaks), or 1825 hours/year only. Cost constraints are not an issue.

3. H2 needs a lot more generation than BSwap (almost twice as much by 2050, and even more at the reference year) to satisfy the same transport demand, and this additional generation will be obtained from wind and sun. This means that the relative fraction of non-dispatchable generation, and therefore imbalance, is much higher in H2 than in BSwap.

4. The consequence of previous paragraphs 1. to 3. is that BSwap will be more effective in balancing the electric system than H2.

5. Finally, for bidirectional support of the electric system in BSwap, all that is necessary is additional, low cost, power electronics (the only fraction of BSS costs unpaid for by transport, in our model). The available power capacity, even if (as considered in this study) much constrained\(^{128}\) to result in negligible battery degradation, is much higher than usually considered necessary for grid support, and for displacement of import/export from inconvenient times of high/low market prices, which should have a significant value. This further decreases costs by management of import/export, and by making it un-necessary to keep other firm reserve power capacity available, and effectively being able to assure frequency regulation, ride through grid incidents and other grid stability benefits.

6. H2 is also capable of bidirectional support of the electric system, but it requires a high cost of investment (because the whole irreversible chain of hydrogen generation, storage, and re-conversion to electric power must be installed) and high operational costs (especially that of energy taken from the grid, due to the low round-trip efficiency of the hydrogen cycle, but also other maintenance and operation costs, from water purification to electrolysis and fuel cell substitution, gas compression, and many others). Also, the response time of fuel cells being much lower than that of batteries, all grid stability interventions that require fast response capabilities cannot be supported by H2.

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\(^{128}\) The restrictions imposed by our model include: only batteries far from full charge are allowed to participate in bidirectional support, the maximum rate of discharge is only 0.1C, and the allowed depth of discharge is restricted to produce negligible battery lifetime degradation. Furthermore, as already mentioned, it will be quite probable that battery-to-grid be totally assured by second-life batteries, which could still lower global costs. Battery chargers would then be unidirectional, with EV batteries acting as a pure flexible load, and second-life batteries would have bi-directional dedicated electronics, working purely as storage devices.
We note again that the grid services in items (5) and (6) were not quantified in this study, and therefore were not included in the values displayed above, nor below in the next Chapter.

Even leaving out such significant contributions, our model predicts a difference in global costs for transport and power, between the H2 and BSwap models, of 7 138 M€/year (3.3% of GNP), as summed up in Table 4.1 below. This very relevant cost advantage of BSwap against H2 in global cost should be partitioned between the two sectors in a less arbitrary way, driven by market and policy, but one may immediately guess that electricity will be a lot cheaper with BSwap than with H2. Assume, for instance, that a half of the difference in cost is used for lowering the cost of electricity for general consumers; then the electric energy with BSwap would cost \( \frac{3569}{70} = 51 €/\text{MWh} \) less than with adoption of the hydrogen H2 model.

**Conclusion**

The conclusion is that an outcome of the BSwap model for road transport is a well-balanced, resilient, electric system, with the cheapest electric energy prices.
IV • COMBINED ROAD TRANSPORT AND ELECTRIC POWER SECTORS

COSTS OF THE COMBINED ROAD TRANSPORT AND ELECTRIC POWER SECTORS

The BSmap model outperforms all others, its costs for transport and power being lower than even those of ICE at a fuel cost of 0.65 €/l, and lower by 3.3% of GNP compared to the H2 model.

We have so far estimated costs separately for each of the two coupled sectors, road transport and electric power, the bridge between them being a guessed average tariff for the cost of electric energy paid by road transport to the power sector. Here we finally combine the two sectors together. The arbitrary choice of a particular tariff for energy is eliminated, and the result is independent of this choice for that peninsula model of sector interaction. Of course, the technical interaction between these sectors is vastly more important than the mere financial component, as we demonstrated above.

Table 4.1, namely its last two rows, summarizes the estimated costs for the combined sectors, and confirms the outstanding results for the BSmap model of road transport relative to all others:

Against the incumbent ICE model, BSmap global costs are estimated as lower than ICE, even at the low cost of fuel of 0.65 €/l, by 0.6% of national GNP (1 350 M €/year). This is due to an interesting combination of several cost components; here we shall just point to one, usually neglected, contribution, the difference between ICE and BSmap in the cost of balancing the future grid, which is worth 0.42% of GNP (898 M €/year). At 1.30 €/l, the relative advantage jumps to 2% of GNP (4 354 M €/year).

Against Plug-in, the relative advantage of BSmap is estimated as 0.6% of GNP (1 180 M €/year), with the indeterminacy of the guessed tariff removed. Once one carefully compares the cost contributions, the conclusion is that the most significant difference is the cost of balancing the future grid, which is worth 0.47% of GNP (1 014 M €/year) in this case. The guessed cost of additional generation should be made more precise by further research work.

Finally, against H2, the relative advantage of BSmap is estimated as 3.3% of GNP (7 138 M €/year). This large difference is due to the combination of contributions detailed in the Table.

A complementary vision of the cost differences is displayed in Figure 4.1. Here we lumped together all the contributions into two only, (1) the “Cost of Vehicles” and (2) the “Cost of Energy”.

The Cost of Vehicles includes the first three rows of Table 4.1, namely

a) The upfront cost of new vehicles,
b) The cost of power items of vehicles not included in their upfront cost (replacement batteries
and fuel cells for the lifetime of the vehicle in H2 and Plug-in, the cost of all batteries in the case of BSwap), and
c) Repair and maintenance (with items in (b) excluded, as before).

The Cost of Energy includes all other contributions (noting that the rows “Energy”, in the road transport sector part of the Table, and “Received from mobility”, in the power sector part of the Table, cancel each other), namely the costs of

a) Infrastructures,
b) Additional generation for road transport, and
c) System balance.

### Road Transport Sector costs (\( \text{M } \text{€/year} \)):

<table>
<thead>
<tr>
<th></th>
<th>ICE fuel @ 0.65 €/l</th>
<th>ICE fuel @ 1.30 €/l</th>
<th>H2</th>
<th>Plug-in</th>
<th>BSwap</th>
</tr>
</thead>
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<tr>
<td>New vehicles</td>
<td>17 250</td>
<td>17 250</td>
<td>18 701</td>
<td>19 580</td>
<td>14 130</td>
</tr>
<tr>
<td>Power items not in new V. (Batts. ...)</td>
<td>0</td>
<td>0</td>
<td>2 723</td>
<td>2 109</td>
<td>7 583</td>
</tr>
<tr>
<td>Repair &amp; Maintenance</td>
<td>8 332</td>
<td>8 332</td>
<td>6 253</td>
<td>4 166</td>
<td>4 166</td>
</tr>
<tr>
<td>Energy</td>
<td>3 003</td>
<td>6 006</td>
<td>2 319</td>
<td>3 373</td>
<td>939</td>
</tr>
<tr>
<td>Infrastructures</td>
<td>0</td>
<td>0</td>
<td>4 531</td>
<td>975</td>
<td>1 274</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>28 585</strong></td>
<td><strong>31 588</strong></td>
<td><strong>34 527</strong></td>
<td><strong>30 203</strong></td>
<td><strong>28 093</strong></td>
</tr>
<tr>
<td>Difference to BSwap</td>
<td>493</td>
<td>3 496</td>
<td>6 434</td>
<td>2 110</td>
<td>0</td>
</tr>
<tr>
<td>Difference/GNP</td>
<td>0.2 %</td>
<td>1.6 %</td>
<td>3.0 %</td>
<td>1.0 %</td>
<td>0.0 %</td>
</tr>
</tbody>
</table>

### Power Sector costs (\( \text{M } \text{€/year} \)):

<table>
<thead>
<tr>
<th></th>
<th>ICE fuel @ 0.65 €/l</th>
<th>ICE fuel @ 1.30 €/l</th>
<th>H2</th>
<th>Plug-in</th>
<th>BSwap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of additional generation</td>
<td>0</td>
<td>0</td>
<td>2 401</td>
<td>1 468</td>
<td>978</td>
</tr>
<tr>
<td>(diff to BSwap)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of system balance</td>
<td>1 010</td>
<td>1 010</td>
<td>773</td>
<td>1 126</td>
<td>112</td>
</tr>
<tr>
<td>Received from mobility</td>
<td>0</td>
<td>0</td>
<td>-2 319</td>
<td>-3 373</td>
<td>-939</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1 010</strong></td>
<td><strong>1 010</strong></td>
<td><strong>855</strong></td>
<td><strong>-779</strong></td>
<td><strong>151</strong></td>
</tr>
<tr>
<td>Difference to lowest</td>
<td>859</td>
<td>859</td>
<td>704</td>
<td>-930</td>
<td>0</td>
</tr>
<tr>
<td>Difference/GNP</td>
<td>0.40%</td>
<td>0.40%</td>
<td>0.3%</td>
<td>-0.4%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

### Total costs of the combined Power + Transport sector

<table>
<thead>
<tr>
<th></th>
<th>ICE fuel @ 0.65 €/l</th>
<th>ICE fuel @ 1.30 €/l</th>
<th>H2</th>
<th>Plug-in</th>
<th>BSwap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Difference to BSwap</strong> (( \text{M } \text{€/year} ))</td>
<td><strong>1 351</strong></td>
<td><strong>4 354</strong></td>
<td><strong>7 138</strong></td>
<td><strong>1 180</strong></td>
<td><strong>0</strong></td>
</tr>
<tr>
<td><strong>Difference/GNP</strong></td>
<td><strong>0.6%</strong></td>
<td><strong>2.0%</strong></td>
<td><strong>3.3%</strong></td>
<td><strong>0.6%</strong></td>
<td><strong>0.0%</strong></td>
</tr>
</tbody>
</table>

**TABLE 4.1** The combined costs of the coupled road transport and electric power sectors.

One interesting point revealed in Figure 4.1 is that the Cost of Vehicles is remarkably constant for the different transport models, the slightly higher cost in the case of H2 relative to Plug-in and BSwap being essentially the difference in the estimated Repair and Maintenance contribution.\(^\text{129}\)

\(^\text{129}^\) Unlike the present situation, when e.g. the upfront cost of a hydrogen powered vehicle would be much higher than that of an ICE vehicle. Note that we used the interim technology evolution forecasts, e.g. expected in the Roadmaps for hydrogen technology, which foresees a precipitous fall, from present, in the costs of hydrogen technology.
Most of the higher cost of the H2 model against BSwap comes from the Cost of Energy, the highest contributions coming from the costs of Infrastructures (the heavy costs of production, storage, distribution and dispense of hydrogen) and Additional Generation (due to the low efficiency of the H2 cycle), with a smaller contribution of the cost of system balance (which is much less in H2 than in Plug-in but cannot match the performance of BSwap), as may be tracked down in Table 4.1.

FIGURE 4.1 The combined costs of the coupled road transport and electric power sectors, split into the Cost of Vehicles and the Cost of Energy (both in M€/year, referred to the scale on the left-hand axis). The difference to BSwap of the sum of both contributions is represented as a percentage of GNP, referred to the scale on the right.¹³⁰

These are essential features of technology, difficult to be overcome in the hydrogen processes unless a series of unforeseen (not included in present roadmaps for hydrogen) technological disruptions occurs.¹³¹

As mentioned before, two main contributions to costs are absent from this study:

1. Grid services (beyond imbalance mitigation, as explicit in the previous Chapter), and
2. Ease of use in transport (important for all vehicles, but specially for the logistics of the heavy ones).

Both would favour BSwap and H2 models relative to Plug-in.

¹³⁰ A value of 214 thousand M€ for the Portuguese Gross National Product (GNP) was used. Note that there is no quantitative relation between left and right scales: 3% GNP is not 15 000 M€.

¹³¹ One possibly relevant technological advance may have been revealed recently (2022), by Australian researchers, and taken up by Hysata, which may boost hydrogen electrolyser efficiency to >90% (HHV), a promise of a significant step towards lower cost green hydrogen. At a completely different level, the entire chain might be disrupted by an extraordinary event such as the emergence of large-scale exploitation of natural hydrogen (originating in continuous geological reactions).
Another contribution to society, even more difficult to quantify, is the speed of the transition: how can we value a faster reduction of emissions and of the transition to a new economic reality? We leave a possible quantification to experts in this field. Here we simply state that, in our opinion, the BSwap model for road transport would promote the fastest rate of transition (namely due to social acceptance, ease of vehicle use, and lowest costs) and therefore again outperforms all others in this respect.

**RELATIVE ADVANTAGES OF H2, PLUG-IN AND BSwap MODELS**

*We list a series of issues and analyse the foreseen outcomes for each of the transport models.*

<table>
<thead>
<tr>
<th>Technology model for e-mobility</th>
<th>H2</th>
<th>Plug-in</th>
<th>BSwap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>All vehicles are powered by hydrogen fuel cells</td>
<td>All vehicles are battery electric, and charge by connecting vehicles to power sockets</td>
<td>All vehicles are battery electric, but swap batteries at service stations where charging is centralized</td>
</tr>
<tr>
<td><strong>e-mobility adoption</strong></td>
<td>Slow (due to technical development needs and high costs)</td>
<td>Fast, but incomplete, for private light vehicles; very difficult for heavy vehicles, particularly for commercial long-range</td>
<td>Fastest and complete adoption, once standards are accepted; no big technology barriers; easy to apply in heavy, long-range vehicles</td>
</tr>
<tr>
<td><strong>Ease of use</strong></td>
<td>Good autonomy; ease of supply dependent on number of dispensing stations; acceptable time to refill of about 15 minutes for heavy vehicles</td>
<td>Good autonomy (in near future already); acceptable ease of use for short distance commuter traffic, difficult for long-distance travel, very difficult for heavy long-range vehicles (logistics vs time to charge, very high-power connections and danger of battery degradation)</td>
<td>Good autonomy; refuel as easy and fast as present-day ICEs (a few minutes time to refuel; no worries about readiness, availability, time to charge, autonomy) for all vehicles</td>
</tr>
<tr>
<td><strong>Impact on electric grid: additional energy needs for e-mobility</strong></td>
<td>~70 % in future grid (~100 % of the present one) due to the low efficiency of the hydrogen cycle</td>
<td>~30 % in future grid (~40 % of the present one) due to the high efficiency of the battery cycle</td>
<td>~30 % in future grid (~40 % of the present one) due to the high efficiency of the battery cycle (slightly better than Plug-in because it avoids fast charging altogether)</td>
</tr>
<tr>
<td><strong>Impact on electric grid: balancing services</strong></td>
<td>Good balancing effect because demand by hydrogen production plants is flexible. By-directionality not possible from vehicles, only in purposely built hydrogen facilities (with high investment in new electrolyser, fuel cell, power electronics), Power capacity limited by economics.</td>
<td>Very limited balancing effects, even with introduction of flexible demand and V2G</td>
<td>Excellent balancing effect, being a flexible load to a larger degree than hydrogen. Bidirectionality is easy and unexpensive (power electronics only). Capable of acting as firm power reserve, of contributing to frequency regulation, incident ride-through, .... Power capacity virtually unlimited by cost.</td>
</tr>
</tbody>
</table>
## The Transition

Why we need battery swapping for the future energy and transport systems

<table>
<thead>
<tr>
<th>Technology model for e-mobility</th>
<th>H2</th>
<th>Plug-in</th>
<th>BSwap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Battery management 1.</strong></td>
<td>No need for fast charging.</td>
<td>Fast charging unavoidable:</td>
<td>• No fast charging: batteries are</td>
</tr>
<tr>
<td></td>
<td>High short-cycle rate (fuel cell</td>
<td>• Lower battery life</td>
<td>charged at low rate, in a controlled</td>
</tr>
<tr>
<td></td>
<td>to battery, battery to motors)</td>
<td>• Less efficient use of energy</td>
<td>environment:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Need for powerful battery</td>
<td>• Longer battery life</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cooling strategies for high</td>
<td>• Efficient use of energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>power charging (an especially</td>
<td>• No need for special battery cooling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>relevant problem for heavy</td>
<td>for high power charging</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vehicles)</td>
<td></td>
</tr>
<tr>
<td><strong>Battery management 2.</strong></td>
<td>Battery quality control, re-use</td>
<td>Battery quality control, re-use</td>
<td>Battery quality control, re-use and recycle</td>
</tr>
<tr>
<td></td>
<td>and recycle less simple than in BSwap.</td>
<td>and recycle less simple than in BSwap.</td>
<td>easily performed (BSwap has the equipment and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>the know-how for quality assurance, and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>automatically classifies batteries as fit for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EVs, for second-life, or for recycling).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Better use and recyclability of materials.</td>
</tr>
<tr>
<td><strong>Battery management 3.</strong></td>
<td>Battery replacements usually necessary during vehicle lifetime</td>
<td>Vehicles suffer from battery degradation; battery replacements usually necessary during vehicle lifetime</td>
<td>Vehicles enjoy continuous renovation of batteries, with technology improvements. Battery lifetime is decoupled from the vehicle .</td>
</tr>
<tr>
<td><strong>Efficiency in use of equipment</strong></td>
<td>Equipment (electrolysers at hydrogen plants,</td>
<td>Chargers are dispersed, self-contained</td>
<td>Highly efficient use of equipment:</td>
</tr>
<tr>
<td></td>
<td>fuel cells in vehicles or in closed-cycle</td>
<td>pieces of equipment: expensive to install and</td>
<td>• + Batteries have double use, as mobility</td>
</tr>
<tr>
<td></td>
<td>storage, ...) are dedicated to their single</td>
<td>maintain. Batteries are on-board, their use</td>
<td>providers and as grid managing devices</td>
</tr>
<tr>
<td></td>
<td>aim, are not amenable to double use as in</td>
<td>as a grid asset limited by non-decoupled</td>
<td>• + Chargers may double as grid manager</td>
</tr>
<tr>
<td></td>
<td>BSwap.</td>
<td>charging from vehicle use.</td>
<td>devices (flexible load providers, bidirectional grid support)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• + Equipment is concentrated in BSSs, so easy maintenance, replacement, ...</td>
</tr>
</tbody>
</table>

**TABLE 4.2** Comparison of a few characteristics of the road transport models H2, Plug-in, and BSwap
V • HOW UNIVERSAL ARE THE CONCLUSIONS?

The conclusions above were obtained by application of road transport models to the electric system of a specific country, Portugal; what can we say about other countries?

We have shown, by applying the three models of decarbonized road transport to a concrete system, that of Portugal in a decarbonized future, and calculating in detail the consequences of each model on the road transport and the electric sectors, that BSwap vastly outperforms H2 and Plug-in.

Portugal was chosen for two reasons: first, because it is the country we know more about; secondly, and importantly, because Portugal represents a common tough problem of evolution towards decarbonized power and road transport systems: that of relying on an electric system almost 100% renewable, and largely dominated by non-dispatchable sources such as wind and solar. Success in Portugal would mean hope of success all over the world.

It is quite possible that the best way to a decarbonized future of many countries in the world, presently relying heavily in fossil generation, might be the path that Portugal undertook, aiming at a very high-renewables energy mix.

However, the formidable problems of cost and energy security that many predict for a high-renewables path might steer these countries away from assuming it, and steer them into alternative paths. The demonstration that the BSwap model we propose works, and that it may indeed be the lowest cost alternative both for transport and for electricity, should encourage many countries in the world to study, and possibly choose, this path.

Portugal was therefore seen from the start as a difficult case from the point of view of electric system stability, with no nuclear power, a hydropower generation that would satisfy only 10% of future needs, and 85% of its energy coming from variable, non-dispatchable, sources (wind and solar), which we made even more stringent by the model assumption that no gas turbines would remain in service\(^{132}\): can we succeed, under such circumstances? This is the reason we placed much emphasis on grid balance, and were surprised by how well the BSwap model, together with hydro resources (particularly pumped storage), could balance the grid, and demonstrate lowest costs for the combined, fully decarbonized, sectors of power and road transport.

Let us now look at other countries. The question now is: how different are their energy matrices? Would BSwap still be the best choice for most of them?

\(^{132}\) Which we shouldn’t do in a hurry. It would be safer to keep natural gas for some time but reducing its use from the present >30% down to a very few percent only; the cost of keeping this option open would not be a problem, since the gas turbines would be totally amortized by then, and the maintenance and operational costs should be tolerable. The impact on emissions reduction would be already very high, even if we didn’t zero them immediately; and we could turn off gas entirely only after we felt sure that, after years of experience, it was not needed (or substitute fossil for renewable gas).
The first point to note is that road mobility must be weaned from petrol, and the large-scale options for doing it narrow down to essentially the three models we discussed. Very generally, it is always a good idea

- to (a) turn into a flexible load a large part of total demand and to (b) offer bidirectional flow of power, because these two characteristics will contribute to stabilize the grid, give it reserve power, and generally decrease the cost of electricity and of transport
- to offer ease of use and the possibility of full decarbonization of all vehicles, including the heaviest
- to choose high energy efficiency processes, that lead to lower investment, impacts and costs, and
- to better manage equipment and materials, diminishing cost and impact.

In fact, all the benefits listed in Table 4.2 remain valid whatever the electric system. Now the numerical values for the improvement of grid stability that can be reached, and the calculated costs, will indeed change for the different energy matrices of each country or region. For instance, BSwap is excellent in help balancing the grid in the time scale of one day or up to a very few days, and this is responsible, together with water pumping storage, for success in balancing the future grid in Portugal. For countries which rely on hydropower, balance is probably not a big issue, so will BSwap still outperform Plug-in? The answer lies on which services each model may provide, both on mobility and grid impact, and requires finer modelling. Another issue is the degree of road transport decarbonization that BSwap will allow in the mid-term, which of course depends on how amenable to decarbonization the power system is. All these are reasons why we encourage experts from other countries in this field to explore the possible outcomes of application of the BSwap model to their regions and compare them to the alternatives.

Notice that present matrices are a starting point only: the relevant ones will be the result of their evolution in the next decades. This evolution will be subjected to the pressure to decarbonize and to the policies that will try to achieve objectives that are technical (such as a stable power system with energy security, and a road transport system that achieves its aims), environmental, social, and economic (a minimum cost solution).

Let us therefore explore and speculate on a few relevant (because of their size or because they are extreme examples) countries or regions and start by looking at the status and recent evolution of their electric power matrices.

**Status and trends of electric energy matrices**

We start by analysing a few significant electric energy matrices.

**Portugal**

Since Portugal was our case study, we comment first its electric energy mix evolution, Figure 5.1, until 2021. Coal and oil, which reached 80% of total generation in the 1990’s, are now zero; gas is less than 50%. In the last two decades, renewables have compensated the decrease in fossils and powered the slight growth: wind exploded 2004-2014, solar is starting to explode now. Wind and solar are expected to grow much more, to ≈85% of a total generation that should grow to accommodate the increasing electrification of the economy, particularly transport, in the long term. A BSwap model for future transport is shown above to allow this further transition at a minimum cost.

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133 The only question being on the relative cost of Plug-in vs BSwap in the last row of the table (no question on H2).

134 All the data on the electric mix presented below were obtained from https://ourworldindata.org/electricity-mix (by Hannah Ritchie and Max Roser).
FIGURE 5.1 Electric energy mix in a few European countries. The units in the vertical scales are TWh.
Spain

The Spanish mix is strikingly similar to that of Portugal, the main difference being the nuclear fraction of 20%. Fossils are now 1/2 their maximum in 2008, and ≈1/3 of all generation. The results of applying the mobility models to Spain in the future should produce very similar outcomes to those demonstrated in Portugal. Note that this similarity strongly supports the idea, explored above, that import/export, in situations of dire need, would be ruinous for Portugal.135

However, similarity is not the absolute rule. We present two countries that represent extremes in Europe:

Two extremes: France and Austria

France is the country in the world with the highest nuclear fraction, ≈70%. Fossils are only 9%, renewables (particularly solar and wind, hydro being stable at only 10%) have grown to 20%, helping to keep total generation constant without recourse to more fossils.

Austria, on the contrary, boasts hydro at 60%, other renewables have grown to almost 20%, about the same as fossils, and no nuclear.

Germany

Germany’s energiewende intense effort helped renewables to reach 42% (despite a minuscule contribution of hydro), substituting dwindling coal and nuclear contributions: fossils and nuclear were ≈95% until 2000; fossils are now down to 46%, and nuclear to 12%.

European Union (27)

The EU evolution in the last two decades can be approximately described as

- A constant total annual generation of ≈2 800 TWh,
- With substitution of the drop of coal, oil and nuclear of ≈730 TWh
- by the growth of non-hydro renewables by the same amount.

Total fossil generation is only 36%, and decreasing, while renewables, at 1 070 TWh, are already 38% and increasing. Nuclear is 26% but decreasing.

Consider now relevant examples from the rest of the world (Figure 5.2). The two national largest electric systems are:

China and the USA

The energy mix evolution of the USA is comparable with that for Europe, with a constant annual generation of ≈4350 TWh, and a drop in coal generation by ≈1200 TWh compensated in almost equal parts by the growth of non-hydro renewables and that of gas. Fossils are still ≈60%, nuclear and renewables about 20% each.

China, with the largest electric system in the world since 2009, presents a totally different graph:

- The most striking feature is the extraordinary rate of growth of generation, at an average rate of some 480 TWh/year in the recent past, reaching almost a total of 8500 TWh in 2021.

135 We stress again that trade will always be beneficial for both countries, exploring whatever complementary opportunities exist for generation or storage in the neighbouring country. However, we cannot expect trade to solve the large-scale balance problem in mostly synchronous neighbours.
Coal generation is 5340 TWh in 2021, and still growing (although at a lesser relative rate than nuclear and renewables), representing still 63% of all generation.

Hydro has grown to 1300 TWh/year (15% of total), wind and solar, in only about 10 years, to 983 TWh (12%), while nuclear, at 410 TWh (5%), is growing at a lower rate.

**India**

India also reveals a fast growth of electric energy generation, reaching 1700 TWh in 2021. It is an even more extreme case of reliance on coal than China: at 1270 TWh/year, coal represents 74% of all generation (all fossils 78%).

Nuclear is 2.6%, hydro is only 9%, all renewables account for 332 TWh, or less than 20%.

**Brazil**

Brazil’s energy mix is very different from that of India, and quite similar to Austria:

- Total generation was 654 TWh in 2021, growing at an average of 16 TWh/year in the past 20 years.
- Hydro accounts for 55%
- Fossils account for 20%, nuclear for 2.2%
- Non-hydro renewables, at 144 TWh, represent 25% in 2021, and are the fastest growth contribution to generation, having increased almost 110 TWh in the last 10 years, responsible for most of the increase of 122 TWh in total generation in that period.

**OECD and Non-OECD**

A more global picture can be obtained considering the world energy mix divided into OECD countries and Non-OECD countries.

The global energy matrix of OECD countries is characterized by

- A constant total generation since 2007, stabilized at 11 000 TWh/year.
- Coal generation has fallen by 44% since that year to 2 250 TWh in 2021, oil nearly disappeared, but gas grew by 970 TWh to 3 270 TWh in 2021, compensating part of the loss by coal and oil: total fossil generation decreased by 1160 TWh to 52% of total in 2021, from over 63% in 2007
- Nuclear fell by 17.5%, a loss of 400 TWh from 2007 to 2021, and is now 17% of total
- The drop in fossils and nuclear of 1560 TWh was compensated by a similar growth of non-hydro renewables, half of it due to wind, in the same period; renewables are now over 30% of total, up from 16% in 2007.

A totally different evolution is observed for the Non-OECD countries:

- Total generation has been growing at an average fast rate of 565 TWh/year in the past two decades, reaching 17 200 TWh in 2021 (after passing the total generation of OECD countries in 2011)
- All forms of generation are growing, except oil:
  » Coal, at 8 000 TWh (46.5% of total), is growing 252 TWh/year
  » Gas, at 3150 TWh (18.3% of total), is growing 116 TWh/year
  » Nuclear, at 890 TWh (5.2% of total), is growing 38 TWh/year
  » Renewables, at 4580 TWh (27% of total), are growing 230 TWh/year

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136 In an absolute scale, in the last few years in China, coal is increasing by some 200 TWh/year, renewables at the same pace, and nuclear by only 38 TWh/year.
FIGURE 5.2  Electric energy mix in a few selected countries and groups of countries. The units in the vertical scales are TWh.
Now that we overviewed the variability of electric energy matrices and their present trends, the next step should be to study and compare, for each country or region, the impacts of road transport electrification resulting from each of the three decarbonized road transport models, including the changes in emissions, in the transport and power sectors, and the costs. We urge researchers and decision makers to assume this undertaking, which is presently well beyond our capabilities.

We shall therefore limit our analysis to trying to deduce qualitatively the possible outcomes of the three road transport models on different electric types of systems, examining a few of the issues raised by transport electrification.

Note that this cannot be decoupled from the future evolution of energy matrices, and while we may guess where OECD countries are heading to, it is still quite difficult to imagine how most non-OECD countries will evolve (will they follow a path similar to that of OECD countries?), and how fast. Energy matrices are known to evolve slowly, namely because investments take a long time to be approved, realized, and amortized, but, on the other hand, the relative weights within a given matrix are easier to change in systems with fast growth, because the change is realized through shifts in new capacity, rather than wait for the replacement of old capacity.

Therefore, it makes sense that the issues be faced and discussed immediately.

**Will primary energy consumption increase or decrease in the future?**

*Primary energy consumption is still slowly increasing, but this might be reverted soon with no loss of quality of life. On the contrary, gains in quality of life are compatible with a decrease of primary energy consumption.*

Let us start by considering primary energy, the energy we get from the sources, such as oil, coal, gas, or hydroelectric, solar or wind energy. Its consumption has been growing in the past years at an average rate of some 2%, but this number doesn’t reveal the profound changes that are happening. One indicator is that fossil fuels were 85% of primary energy in 2016, in 2021 only 82%, the main cause behind this being the growth of renewables. We expect a faster change soon, with primary energy consumption starting to decrease, the main driving force being the following:

1. Primary hydro, wind or solar energy is electric; if it displaces, for instance, coal generation, then 1kWh of renewables substitutes 2.5 kWh of coal (the result of an average conversion efficiency of 40% for a coal-powered electricity generation plant);
2. If you electrify road transport, the result is approximately the same: 1kWh of renewable electric energy fed to an electric vehicle avoids the consumption of about 2.5 kWh in the form of diesel or gasoline.

The trend is not to diminish the benefits of energy consumption at all; on the contrary, our global aim is to increase them: we are simply shifting into higher efficiency technologies, which happen to avoid emissions as well. The benefits of energy should extend particularly to the energy starving communities, but this can be done with a reduction of emissions, and even also of the total primary energy consumption, if the increase of final energy consumption \(^{137}\) is more than offset by increased efficiency.

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\(^{137}\) It is possible that quality of life be maintained with lower final energy consumption, in developed countries. However, presently, at the stage of energy hunger of many in the world, it is unavoidable that final energy consumption increases.
Electrification of our economy, with higher incorporation of renewables, is a path we aspire to achieve.

**Will electric energy consumption increase or decrease in the future?**

*Electric energy consumption is bound to increase in the foreseeable future.*

The human development index (HDI) follows most closely the electric energy consumption per capita up to about 4,000 kWh/year. Societies with much lower consumption have invariably poor HDI, which is raised sharply until the value cited above is reached. For higher values of consumption, the HDI still increases, but more slowly. Let us then use this value of 4,000 kWh/year.capita as a desired threshold to be attained by all societies.

Now the total electricity consumption by OECD countries, at 11,000 TWh, for a population of about 1.35 thousand million, results in 8,150 kWh/year.capita, well above that threshold.

Consider now the non-OECD countries, but subtract China, as its development level is already similar to the OECD average. Then the total electricity consumed, $17,200 - 8,484 = 8,716$ TWh, for a population of about 5.2 thousand million (65% of humanity), gives 1,680 kWh/year.capita, only 42% of the threshold.

Furthermore, this part of our societies is responsible for virtually all increase in world population, since the population of OECD and China is almost constant.

The combination of energy hunger and population growth of this large fraction of humanity is the unstoppable drive for the increase of global electric energy consumption. And as much as we want to decrease emissions, and use ever more efficient technology, we cannot but think of this formidable problem, illustrated above e.g. by the case of India.

**Will transport electrification lead to lower emissions?**

*It depends very much on the energy mix, and on how you do it.*

Road transport is essentially powered by liquid fossil fuels. So, if I give up my diesel car, and buy an electric one, all the emissions from the fuel that would be burned are avoided, right?

The problem behind this question is illustrated by the electricity matrix of a country such as India, an example of an electricity mix with a high fraction of coal generation. Electrification of transport will reduce oil consumption, but applying it blindly might well increase, not decrease, global emissions, due to the heavy reliance of electric generation on coal.

We can easily guess that electrification through hydrogen, without any further adjustments, would in fact increase emissions, due to its inefficiency, its demand on the electric system being satisfied almost ¾ by coal.

It is also possible to guess that Plug-in or BSwap models for road transport might just decrease emissions, due to their higher energy efficiency: the increase of coal emissions might be more than compensated by the decrease in liquid fuel emissions (particularly because coal is a fraction of all generation, not 100%), even with the relatively low coal plant efficiencies. However, we are simply substituting the low efficiency of a diesel motor for the low efficiency of a coal plant; put in the losses, and you may find that emissions have slightly increased, instead of decreasing. The gains, if they exist,

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138 In a more detailed study, this value might be corrected for regional conditions, such as climate.
are therefore marginal: we would still be far from decarbonized transport.

Is there a way of changing this equation?

**A model path to decarbonization**

*How to progressively decarbonize energy in a country such as India, which presently relies massively on coal for electricity? We look for ways of installing new decarbonized capacity which may be fast to realize and make economic sense: not too high an investment burden, with fast returns, and an eye in the future.*

How could we devise a promising road to accelerate the simultaneous decarbonization of power and transport in a country such as India?

When we look for a solution, the first point we admit is that (contrary to most OECD countries), the priority in India should not be to substitute existing coal plants, but rather to concentrate on new generation.

The reason for this is clear: with total electric generation in India at 1 600 TWh, and a population of 1.4 thousand million, the annual electric consumption per capita is only 1 140 kWh, very much below the desired threshold of 4 000 kWh. To approach it, India needs to multiply present generation by at least ≈3.5 139. In other words, the new generation capacity that needs to be installed is much higher than the existing capacity. Therefore, the focus of decarbonization should be the new capacity, rather than trying (with financial losses to the investment already made) to substitute existing generation.

Of course, we dare not tell India what it should do. Besides, India was chosen simply as an example of a difficulty common to many other countries.

The aim of this sub-chapter is rather to show a possibility that might have visible impact on the energy and transport sectors of such a country, and was probably overlooked, simply because the battery swap model has not been present in energy planning studies.

**A possibility**

Perhaps one possibility of igniting transport electrification might be local refuelling stations, along a few main roads, associated with locally available renewables (e.g., solar, wind, or others) that would be used with priority preferably to the grid. This model would be best adapted to H2 or BSwap models (and less interesting for Plug-in 140), and the use of a renewable-rich power would be certain to decrease emissions. Notice that this refuelling substitutes high-cost diesel or gasoline, so it is possible to guess that the economic balance would be favourable. Benefits to the local grid (balance and support) might be a welcome spill-over. Between the two models, BSwap would probably prove the lower cost, not only in the long-term, when BSwap would be definitely cheaper, but also in the short-term.

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139 Probably rather more than this, if you model population growth and the increasing electrification of economic activity, including mobility.

140 The reason is that in BSwap and H2 most of the local renewable generation can be used for charging the batteries, or for hydrogen production, and vehicles receive the energy accumulated for the past hours when they refuel. On the contrary, in Plug-in the demand is immediate when a vehicle stops for refueling (and may recharge using a lot of national grid energy, instead of local generation, which is unable to supply enough at that precise time). During the rest of the time the local generation is not used for transport, it just injects power in the grid, and its deployment is therefore limited by imbalance.
An illustration of the model

We shall explain the basic idea using a simple example of its application, illustrated in Figure 5.3, for a BSwap model. (We are certain that many other possible applications will be devised, based on similar ideas.)

The town shown in the map, and the region around it, are served by a highway, and electric energy is supplied by a line of the national transport grid, which branches out from the substation into several intermediate voltage lines of the distribution grid. Electricity consumption is low but growing, the transport line has a lower capacity than needed, and the quality of the electric energy supply is low, partly because of increasing demand, to which the grid has been too slow to respond to. The answer could be the new regional coal power plant (long planned and promised), and investment in doubling the capacity of the transport and distribution grid, so it might supply the increasing consumption in peak times. The installation of an increasing capacity of local renewable generation was considered, but adoption was held at a minimum: the grid balance problems were far too expensive to solve via installation of storage capacity, and the connection to the national grid much too weak to respond both to peak generation and to peak consumption.

We suggest an alternative. Suppose that

- The battery swap model for road transport is adopted.
- Modular battery swap stations are progressively installed in the old fuel stations,
  » some of them along the highway, some 30 km apart each other, mostly to serve the long-distance transport, namely heavy trucks and buses, but all other vehicles as well,
  » others around (or in) the town, most frequently used by buses, taxis, and all other electric vehicles that serve the local population.
- Local renewable generation is also progressively installed, much of it close, and directly connected to, the battery swap stations. Local renewable generation rapidly grows to new,
previously thought impossible, capacities. In fact, installed renewable capacity becomes enough to supply with electric energy all transport demand, and to supply much of the town and regional consumption.

- Local grid capacity and generation expands without having to wait for very large, far-away, investments in centralized plants, and is decided and managed locally.
- Energy quality becomes high, with a stable and resilient local grid. The national transport grid line continues to be used but is not congested anymore: there is no need to invest in doubling its capacity. In fact, total local consumption soon more than doubles, but the same old line capacity is found to be sufficient. Energy is being brought into the region, or exported to the national grid, but not at rush times of peak demand or generation: just a continuous modulated flow, kept below line capacity.
- High quality and low-cost electric energy attract new activities, and the old fossil fuel powered activities are progressively electrified. Quality of life improves.
- Emissions due to regional transport, fuels, and electricity consumption are on track to become net zero.

How is this possible?
The reader may have guessed that all we suggest here is an application, to this region, of the BSwap model previously applied to the test country, Portugal.

The model makes economic sense, namely because

- With the BSwap model, substitution of high-cost, liquid fuel based, road transport, for the lower cost electric option brings about fast returns;
- The capacity of BSSs to balance the local grid allows the installation of large capacities of cheap, local renewable generation, no energy being curtailed or exported at low cost;
- Most of the cost of this balancing capacity (both investment and operational) is paid for by mobility, so the resulting stable, resilient grid supplies quality electric energy at a low cost to consumers.
- High-cost investments in new centralized generation capacity, and in high-capacity long power lines, are avoided.
- Access to cheap, high-quality electricity will help attract economic activities that shy away from poor electric services.

These excellent outcomes are the result of the merge of transport and of general energy needs into a single electric system, using the battery swap model. The high renewable fraction is made possible by the flexibilization of transport demand and by the bidirectional local grid support by BSSs when needed. The role of the line connecting the region to the national grid isn't anymore to satisfy all regional energy needs, but mostly to supplement and help balance the local grid. It could, for instance, play the role that hydro pumping storage played in the Portuguese example (with its bidirectional flow of energy), plus the cross-border seasonal balance. The combined power of these two components might be less than 1/2 of peak consumption. These grid balancing components require a line connection with much lower capacity than a line to supply all power to the region, which would have to be designed to satisfy the peak demand.

All this depends, of course, on the regional conditions, namely which renewable resources are
cheaper and abundant, and which may best satisfy the perceived needs. The example above referred to a region with good local renewable resources, offering an opportunity to simultaneously decarbonize and increase quality access to power; such regions should, of course, be prime targets for this transition. The local demand profile should also be taken into account, since it may vary regionally (due e.g. to different transport and heating/cooling needs, or type of industrial activity). Therefore, when planning energy systems, it would be a mistake to try to use the same solution all over: which combination of solar, wind, waste/biomass, hydro, ..., resources are best, varies from region to region.

Note that our intention is just to point out this possibility, opened by the battery swap model, of progressively integrating transport into a progressively decarbonized electric energy system.

However, none of this may be achieved without central government decisions, since, of course, the BSwap model is not the venture of a small region, it must be adopted as part of a national policy.

**Is this model limited to mostly coal-powered countries?**

No, in fact it is applicable to virtually all countries in the world.

China also relies still very much on coal, and, just as India, it will take some decades to decarbonize, but differs from India in that it is already the country with the world highest rate of renewable power deployment. China is also in the forefront of testing different solutions to the road transport problem, including battery swapping and hydrogen. We therefore think that the model devised above could well be a template for an even faster transition, with high deployment of renewables, and all the benefits described above, in China.

However, once we consider the outcomes of the example above, we start to wonder: could it not be a good model to apply in countries such as the USA, or Australia? How about African countries? And then you realize that, with adaptations to local realities, the model or its variants are in fact applicable to virtually most countries in the world, in some perhaps as a form of ignition, in others the result of mature global design.\(^{141}\)

**How will BSwap fare in countries where grid imbalance is not a problem?**

In most countries, presently, imbalance is not an issue. In several of them, such as Austria, Sweden or Brazil, their electric systems have a large fraction of hydropower generation, which allows balance to be achieved relatively easily. Other countries have a large fossil-based generation and have presently no great system balance issue; it will come up later, of course, as decarbonization progresses. The question we want to answer is: in such countries, would BSwap still be the best model for road transport?

When grid balance is not a big problem that searches for a solution, road transport models must be chosen looking into the future and considering the other impacts.

If we consider the H2 and BSwap models, their main present impact in the electric system of such countries would be a high fraction of flexible load and the offer of firm reserve power locally (in decentralized hubs, the BSSs, in the case of the BSwap model; in electrolyser plants for hydrogen, with flexible demand and bidirectional power but at the higher cost, lower efficiency, fuel-cell

\(^{141}\) As would be the case e.g. in the Netherlands, with its small size, high population density, very high connectivity of the electric grid, and intensive occupation of territory: we think that, in such a country, energy and transport systems with a BSwap model should be designed globally, not in a regional basis, even including local microgrids loosely connected to the main grid, which are being studied and should be considered.
electric generation for reserve power), which are always interesting. Choice of a model must be made considering the future and based on detailed calculations of the relative impacts. For instance, while it is relatively easy to discard H2 as always a higher cost solution than BSwap, it is possible that presently Plug-in might offer a lower cost solution, because the infrastructure cost is lower than for BSwap (or H2, of course); however, if you consider (a) the ease of use (particularly for heavy vehicles), (b) the costs of the transport sector itself, as discussed in Chapter III, (c) local grid services (an increase of electrical supply quality would be welcome in many cases), and (d) look into the future, we are convinced that BSwap will be proven the best option.

Conclusions

We have shown possible paths for the simultaneous decarbonization of transport and power, using a BSwap option, in countries that rely mostly on fossil fuels for electricity generation, and why such strategies may lead to low-cost paths to the model success in virtually all other countries. We have pointed out why, in any electric system, BSwap may always outperform the alternatives.
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Now that we proved the superiority of the BSwap model for road transport and for the electric system, what impacts will its adoption have in industry and other activities responsible for greenhouse effect emissions?

The BSwap model offers industry a stable, resilient electric grid with lowest energy costs. This will cause a major shift in many industries and activities that presently rely heavily on natural gas or other fossil fuels.

Substitution of natural gas: the power-to-gas concept and the electric alternative

The power-to-gas concept for industry will probably have a limited application, in breadth and in time, because much of the competition will not be between hydrogen and natural gas, but rather between hydrogen and electricity, and electricity will win in most cases.

Some countries are considering the substitution of natural gas for hydrogen as a route to decarbonization. This might be done progressively, within the power-to-gas concept, with injection of ever higher percentages of hydrogen into the natural gas distribution system. Present industries heavily dependent on gas for energy would just adapt to the new energy carrier. This is easily done for low hydrogen content, but even 100% hydrogen, completely substituting natural gas, should be possible, with technically feasible adaptations in industry.

Of course, hydrogen, obtained from electric energy by water electrolysis, has a higher production cost than natural gas, and is therefore at a disadvantage in the commercial competition. However, as hydrogen technology evolves, costs for renewable energy generation drop, and carbon emission prices soar, penalizing natural gas, the penetration of hydrogen in industry should come at an acceptable price, if not fully competitive. The expected result: progressive decarbonization of gas-guzzling industries.

There is, however, a weakness in this reasoning, which will be the source of the demise of part of this plan in the long term: in many activities, the real future competition will not be between hydrogen and natural gas, it will be between hydrogen and electric energy.

To explain this, let us first consider the heyday of electric systems dominated by natural gas generation. Because electric energy is produced by alternators powered by gas-fired turbines, the best with energy conversion efficiencies of ≈60%, it is obvious that the electric energy produced must be more expensive than the energy of the gas that was burned to generate it: just from gas consumption, the cost of electric energy would be 167% the cost of gas (because of the ≈40% losses), but then you have to add the high investment and operational costs of the plant. These mostly fixed costs, which must be paid for, weigh on energy price, and the less the capacity-factor (the number of equivalent
hours at full power per year), the more they weigh per unit energy produced.

In short, if we produce electricity from gas, the cost of electricity will be much higher than the cost of gas.

Advance into the future, and the process is reversed: hydrogen gas must now be obtained from electricity in hydrogen production plants and distributed (which requires e.g. water purification plants, electrolyser stacks, power systems, hydrogen storage tanks, compressors and pipelines) with investment and operational costs that must be paid for. Electrolysis efficiency may be high, say even over 85% HHV (if promising technologies prove their worth in the future) but overall system efficiency will be less, and there must be a compromise between capacity-factor and cost of energy for a least cost H2 production (especially relevant when you plan to produce hydrogen from excess generation in electric systems dominated by solar and wind energies).

In short, hydrogen will be much more expensive than the electric energy that was used to produce it.

For hydrogen not to be unacceptably expensive, the trick is the following: obtain electric energy very cheaply, at almost zero costs, at times of power excess in the grid; or use solar and wind to generate it in dedicated facilities in favourable regions; or both, and perhaps governments may help by exempting the producer from grid access tariffs, and by co-financing the investment, or even by assuring a guaranteed (subsidized) tariff for hydrogen. Then the cost of hydrogen might become competitive with that of gas (penalized by heavy CO2 emission costs), and progressively substitute it.

In our opinion, this would be a path to continuous bleeding of the economy. Let us explain why:

1. We are not talking about a marginal, small production of H2, but rather about massive quantities. For heavy road transport alone, the required additional electricity generation would be over 50% of total present generation (recall Figure 1.1); or over 100% if all terrestrial mobility would be hydrogen powered; if we further add the hydrogen needed for the decarbonization of present gas-guzzling industries and other activities (an additional ≈70%), even not counting on further future applications (such as air and maritime transport, where hydrogen could substitute oil, not natural gas, or the replacement of coke in the steel industry), we realize that we are talking about much more than doubling present electric energy generation just to satisfy hydrogen production needs.

2. Such large quantities of hydrogen cannot be obtained from the excess crumbs of the electric power sector as modelled above, they can only be generated by enormously increasing solar and wind electricity generation\(^\text{142}\). Now a reasonable average cost for terrestrial combined solar and wind\(^\text{143}\) generation would be about 45 €/MWh, and projections for off-shore wind energy are usually above this (more expensive than terrestrial wind because of high installation and maintenance costs, which are exacerbated in the case of floating wind platforms, and not sufficiently compensated by the larger capacity-factor of off-shore wind). If we assume hydrogen production will buy “excess” energy very cheaply, the consequence is that electric consumption is that electric

\(^{142}\) In our models, we are for now ruling out nuclear and fossil fuels with carbon capture and storage.

\(^{143}\) In the models used in this work, a small offshore component was assumed: 20% of the wind generation comes from off-shore wind.
energy, for general consumers, will be that much more expensive.\footnote{Assume that the average cost of generation is 45\euro/MWh, and that half of the generated energy is paid by hydrogen plants at an average price of 20\euro/MWh (an imposed low price, needed for hydrogen to be competitive); the other half must be sold by renewable electricity producers at prices over 70\euro/MWh just to pay for basic generation costs. On the contrary, in our BSwap model, “excess” energy is absorbed by battery charging at BSSs, at an estimated average price of 40\euro/MWh, and hydrogen production, for whatever industrial needs, must compete in the energy “excess” market and pay a similar price. Renewable electricity producers may then sell energy for general consumption at only 50\euro/MWh with a profit. Conclusion: this very simple example shows how the so-called hydrogen economy could make electricity generation for general consumers 40\% more expensive than a BSwap model.}

3. Whatever the model for hydrogen generation, be it dedicated generation, grid connected, or hybrid, part of the new generated energy cannot be economically absorbed by the hydrogen plants, because of the large fluctuations of generated power: for optimum hydrogen cost (which requires a high capacity factor), some energy will have to be either curtailed or injected at near zero cost in a grid that will itself be in a state of surplus of power (because wind and solar are also dominant in the grid). This will further increase the average cost of electric energy paid by the hydrogen production industry.

4. Final users still must pay for the storage and distribution costs (higher for hydrogen than for natural gas), and this further increases the sell price of green hydrogen.

5. In conclusion, forget the miraculously low costs of 20 or even 10\euro/MWh for renewable electricity mentioned by some projections of hydrogen proposals as possible acquisition costs for electric energy by electrolyser plants. Hydrogen will cost at least some 40\% over the much higher average electricity cost bought for its production, and this means future values at least of the order of 50\euro/MWh HHV (59\euro/MWh LHV), or 2\euro/kg, for hydrogen gas.\footnote{Just one example, taken from the publication “Path to hydrogen competitiveness: A cost perspective”, published in January 2020 by the Hydrogen Council. They assume that, in the future, technology may have evolved so that a dedicated, very large, offshore wind installation can supply electrolyser with an electricity cost of 33\$/MWh at a capacity factor of 50\%. Then the cost of hydrogen, produced with future evolved technology, might be only 2.6\$/kg (66\$/MWh HHV, or 79\$/MWh LHV). Note how hydrogen results much more expensive than the electric energy used for its production, even at a high capacity factor, and how, even in this best-case projection, the cost of hydrogen is above 2\$/kg.}

6. Even at such prices, hydrogen can be competitive with natural gas, if CO2 emissions costs are sufficiently high and subsidies to hydrogen generous enough.

7. However, the relevant question is not whether hydrogen can compete with natural gas, it is rather: will hydrogen be competitive with electric energy as an energy carrier?

8. The short answer is no. Wherever electric energy can be used, it will be preferred to hydrogen as an energy carrier, because of its lower cost, high efficiency of conversion into any final energy form required, and adaptability. One example of this competition between hydrogen and electric energy was amply studied above, and the conclusion was clear: the H2 model for road transport would cost some 3.3\% of GNP more than the electric option of BSwap. So, at least in road transport, the use of hydrogen as an intermediate energy carrier is a bad, expensive bet.

9. Take heating and cooling in buildings as another example. Will hydrogen substitute natural gas for heating, or will we massively adopt electric heat pumps, which consume, in the form of electric energy, only a small fraction (say, ¼ only) of the thermal energy output, and
simultaneously solve the cooling problem? The answer is obvious. As it will be for many low-temperature industrial processes.

10. But surely hydrogen will substitute natural gas in other industries, which are considered difficult to shift away from gas burning? Take the example of the ceramics or glass industries, which require high-temperature processes, and are presently large natural gas guzzlers: it is not rocket science to adapt their burners from natural gas to hydrogen! A smooth transition is expectable, right?

11. Well, not quite. Once such industries realize how much they will be paying for decarbonized hydrogen gas for their burners, and how electricity is cheaper than gas, they will adapt. In fact, they can use furnaces directly heated by resistive electric elements, which are quite cheap. Or, if they do require hot gas blasting, there are simple electric solutions available (which will further develop to meet industrial needs): for low temperatures, say below 1000°C, think of the hair-dryer concept; for high temperatures, think of methods of direct electric heating of the gas. After all, electric discharges in lamps easily reach 20,000°C, plasma guns and arc furnaces are common in industry, and the technology and cost of this family of devices is easily foreseen as evolving to adapt to industry needs, and provide efficient, low-cost solutions.

12. Once industry considers the electric solution, it suddenly realizes that a new paradigm opens up: if you do not need to burn a fuel for heat, then you do not need a huge flux of fresh air for oxygen to burn the fuel. Therefore, your process doesn’t have to be an open gas cycle, with fresh air in to feed the combustion, and exhaust out of a chimney, spewing particles, nitrogen oxides (NOx) and other pollutants into the atmosphere. On the contrary, the process will evolve into a closed gas cycle: process gas in, process gas out, clean it from pollutants, re-correct its composition, and re-inject into the process. The consequences:

a) A much higher control of the process gas, at a lower cost;

b) Virtually no atmospheric emissions of particles, nitrogen oxides NOx, or other pollutants, and

146c) A much higher energy efficiency can be reached, because there is no need to heat a lot of fresh air from ambient up to process temperatures.

Note that the process gas can be adjusted to needs by mixing in appropriate additives. For instance, you may want a reducing atmosphere; then you may add hydrogen, for instance, but only the quantity needed for the chemical process, not the huge flux to be mostly burned for energy. The same for an oxidizing atmosphere: a small addition of air, or oxygen, may be appropriate. The point to note is that these are chemical additives, used in small quantities in an (almost) closed loop, not the huge fluxes necessary in an open cycle.

In conclusion, the electric solution for natural gas substitution will be generally cheaper, and much more environmentally benign than the power-to-hydrogen solution.

146 One interesting example comes from the glass bottle production industry. While the standard technology relies on natural gas, the glass industry has already foreseen the need, and started already to familiarize with completely gas free, 100% electric, production lines, to acquire know-how, an eye in the future.
Power-to-gas and as a bridging, temporary solution

The arguments above are probably sound in the long term for many gas-consuming activities. There is, however, an opportunity for the power-to-gas concept to produce acceptable results during a period of transition for these activities. A few reasons:

- We expect that the technical evolution of electrolyser plants will lead to higher efficiencies and lower costs; hydrogen energy will always cost more than the electric energy that was used for its production, but the difference in cost at the delivery point might be not unacceptably high;
- Contrary to the case of road transport (where hydrogen energy must be converted back to electric energy and pay a dear price for it), in the use of hydrogen for industrial heat, low conversion efficiency is not a problem, nor the cost of equipment: present burners will be cheaply adapted to hydrogen.
- The shift from gas to electric energy cannot be immediate for several reasons, such as:
  » This shift requires investment, and this is a barrier for many industrial installations.
  » It will take time for many of the technologies needed for this transition to become available, since, in many cases, industrial equipment is tuned only for gas burning, and new electric solutions will take time to develop, to mature and to lower their cost.

For these reasons, we do not expect a sudden rush into all-electric energy, but rather a progressive trend as new industrial installations substitute obsolete ones.

The conclusion is therefore that the power-to-gas concept may be a bridging, temporary solution \(^{147}\), for faster decarbonization, but one which we expect

- to be progressively made obsolete as the electric solutions gain competitiveness in many activities, and
- to be largely limited to hydrogen-to-heat applications, since the low efficiency and high cost of the round-trip power-to-hydrogen-to-power processes, using fuel-cells or gas turbines, limits its applications to the niche markets where e.g. electricity is not available.

The role of hydrogen in the future

Then there are activities that we assume are not amenable to electrification even in the long-term. Some examples are referred in the next sections: air and maritime transport, or the steel, fertilizer, and many other industries that may use hydrogen as a molecule.

These will probably assure a solid, long-term, future for hydrogen, and they are not small-scale applications: large quantities of hydrogen would be required, and it is an interesting question how and where it will be produced and dispensed. However, this is not the focus of this work, so we simply point out a few issues:

- The main source of decarbonized hydrogen is expected to be water electrolysis. Electricity will not be as cheap as hydrogen promoters frequently assume, but high efficiency, reasonable cost electrolyser plants are in the horizon, so hydrogen cost will not be too high, perhaps coming down close to 2 €/kg.

\(^{147}\) One very serious problem for decision makers: how much investment in hydrogen infrastructure, such as new pipelines, and adaptation to hydrogen of the old natural gas network, is justifiable, or a waste of capital?
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- Where will it be produced? Close to the consumption point, or far away, where best renewable resources exist? There are arguments for both options. For instance, long-distance point-to-point hydrogen transport is not too expensive (in fact, in long-distance point-to-point transport, it is far cheaper than dedicated long-distance power lines for electricity\textsuperscript{148} with similar capacity), although much more expensive than that for natural gas, and with a cost of an order of magnitude higher than for liquid fuels.
- Will hydrogen be massively used in these industries, or will they require a transformed molecule, for instance liquid fuels (for which storage and long-distance transport by pipeline have still much lower costs than hydrogen, and are far safer and easier to handle than hydrogen)? And where will this transformation take place?
- One central issue is therefore: will a hydrogen pipeline network be dominant, or will hydrogen be mostly produced, dispensed, and perhaps transformed, locally? Or will the pipeline network be reduced to only a very few point-to-point major pipelines?

Substitution of fossil fuels: the general rule and a few exceptions to it

The general rule: for energy, use electricity; for chemical processes, use the appropriate molecules.

Is the above example for the ceramics and glass industries applicable to other high emission industries? With adaptations to each case, yes. The future rule is the following: for energy, use electricity. For chemical processes, use the appropriate molecules.

Let us briefly look into two of the most difficult industries to decarbonize, and responsible for high emissions:

- The cement industry is responsible for a high fraction of CO\textsubscript{2} emissions for two reasons: (i) it uses carbon rich fuels for the high temperature process (even if some of the fuel is obtained from waste), and (ii) chemical decomposition of the carbonates releases CO\textsubscript{2}, which is an unavoidable, intrinsic consequence of the process chemistry. Of course, we may substitute the carbon-rich fuel for hydrogen, but, just as above, direct electric heating will be lower cost, and have an added interesting advantage: the exhaust gas may then be almost 100\% CO\textsubscript{2}, not diluted CO\textsubscript{2} in a lot of nitrogen (from the fresh air needed for burning hydrogen). This might make it less expensive to use, or dispose of, the intrinsic CO\textsubscript{2} production.
- The steel industry is a high emitter of CO\textsubscript{2} particularly because it relies on coke for heat (with partial burning to produce CO) and for the reduction of the oxidized iron in the ore. Emissions also result from the down-stream processes of transforming iron into final products made of various types of steel. Again, the same rule may be applied: electricity for heating, molecules for chemical processes. Hydrogen may eventually prove to be a good solution for the decarbonized reduction of iron ore, against other possible decarbonized processes, but need not be the major source of process heat\textsuperscript{149}.

Exceptions to this general rule may be found; one that is frequently cited is that of maritime or air transport.

\textsuperscript{148} See, for instance, DeSantis et al., iScience 24, 103495 (2021), https://doi.org/10.1016/j.isci.2021.103495

\textsuperscript{149} The technology for the direct reduction of iron is still immature, but the trend is to use hydrogen as the ore reducing molecule, while most of the energy may be supplied by electricity, e.g. in electric arc furnaces.
Maritime and air transport

While ferry boats (fluvial or maritime) and local aviation may resort to batteries (and might benefit then from the application of a battery swap model), because of the short commuting distances involved, long-distance transport, both air and maritime, is not amenable to such a solution.

For air transport, it is extremely difficult to beat fuel burning. This is because of the very high energy densities of fuels, which carry all the combustion energy but only a small fraction of the mass used in the chemical reaction. The extreme case is hydrogen: burning 1kg of hydrogen will use 8kg of oxygen, or almost 35 kg of air, obtained from the environment (not carried aboard, using up payload capacity).

For maritime transport, weight is less important than volume, but again, due to their high energy volume density, liquid (or liquefied) fuels are extremely difficult to substitute in long-distance maritime transport.

These are two cases where biofuels, or hydrogen, or other fuels, be they synthetic (obtained from electricity) or from a hybrid biological route, may have a case. We live exciting times research-wise here: the evolution of technology will probably point out, in a few years, which are the most promising energy vectors (from hydrogen to ammonia to synthetic or bio or hybrid liquid fuels such as alcohols and oils) for the decarbonization of these sectors.

One note: in our opinion, the use of bio or synthetic liquid fuels in transport should be reserved for these applications, where alternatives are difficult to imagine. Their present use as compulsory mix ingredients into gasoline or diesel oil (e.g. in Europe) has a negligible impact on emissions, a high impact in fuel cost, and a most negative impact in land use, partly in third countries: it is a bad, expensive, dead-end policy (a call to reality: if we were to power road transport in Portugal via biodiesel, over 50% of the countries’ territory would have to be dedicated to energy crops). It may be justified temporarily if it only uses waste (such as waste cooking oil, plastics, or waste biomass), and for acquiring technological expertise; it should never extend beyond this, it should not justify e.g. land use for energy crops. The resources spent on it might be used with much higher returns in the decarbonization of electricity generation and of the road transport sector by initiating the application of a BSwap model, with an objective that is far more ambitious, aiming at the total decarbonization of the two sectors, something that is known to be impossible, and ruinous, using bio or synthetic fuels. The focus should be air and maritime transport only.

Buildings

Other energy consuming, greenhouse gas emitting, activities will fall on the general rule.

One obvious example is the use of energy in buildings. Heating is still highly dependent on fossil fuels, particularly on natural gas. However, when decarbonization sets in, the offer, by the BSwap model, of low-cost electric energy, less expensive than decarbonized gas (hydrogen, or partly decarbonized mixtures of hydrogen, biogas, and natural gas), will make the obvious shift to electric, highly efficient,
heat-pumps, with complete substitution of fuel burning and complete decarbonization of the heating and cooling of buildings. Again, the Battery Swap model will promote the fastest transition in energy use in buildings, through its offer of a stable, resilient grid, with least cost electric energy.

**Conclusions**

Perhaps the idea that, for energy, you must burn something, is still collectively ingrained in our minds from pre-historic times, and that may be the reason why sometimes it seems difficult to face obvious alternatives.

It took a long time to stop burning fuels for lighting, but the transition was mostly done by mid-20th century, and we no longer associate lamps to olive or whale oil.

For cooking we are in the middle of the transition: somewhere between gas or wood burning and electric (microwave, induction, or resistance) heating. The same is true in many more sectors: from home heating to cars, the electric alternative to fuels is becoming ever more present.

However, in many studies by experts on energy, we are often reminded of the subjacent association of energy with fuels that seems to come to the surface: something must be burned.

By considering the alternatives, we hope to have convinced you, perhaps against ingrained mind associations, that electric energy will be all dominant in the future of energy 152.

Forget hydrogen as a major future energy carrier, and the much-touted hydrogen economy. Hydrogen, as an energy carrier, may play a bridging role in the partial substitution of natural gas, but in the long-term it will be limited to niche applications, although some very significant in volume (such as air and maritime transport as discussed above). On the contrary, hydrogen has probably a bright future as a molecule, a chemical that may be more massively used than in the present in several industries, such as steel making and fertilizers. However, hydrogen will be produced in market competition with others for low-cost electricity, and it will not be cheap.

We hope to have convinced the reader that the Battery Swap model for road transport extends its outcomes well beyond transport, and will prove to be the most socially acceptable, cheapest, and fastest route to a deeply decarbonized society.

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152 Let us not demonize coal, gas, or oil, however. We reached the present heights of civilization on the back of fossil fuels. We own them that, even if wars were fought over them, and climate is being altered by their excessive use. And there is no sin in considering their continued use in niche applications, such as air and maritime transport, until other solutions become viable and competitive. It is simply time to move over, to the new energy systems, hoping that our choices are intelligent enough to allow us to continue our way to human development and freedom.
VII • PUBLIC POLICY

Public policy is needed to foster the most socially acceptable, fastest, and lowest investment path to the deep decarbonization of our economy offered by the Battery Swap model.

So far, we have offered a vision of a future, and we hope we have convinced the reader that the Battery Swap model for road transport outperforms all alternatives for the transport and the power sectors, and that its outcomes spread into many other activities, with far reaching consequences. Its future world will be more affluent, cleaner, and happier than the alternatives.

The question now is: How do we get there? How can public policy help us progress along a minimum cost, fastest track?

It is possible that we might reach the described future without any specific purpose in the mind of public policy makers, just from the interplay of social forces, but the path would not be straight and fast, and a lot of resources and time would be wasted on wrong, dead-end solutions. Or maybe the several paths that spontaneously appeared, having been already travelled too far, for too long, could be such that the cost to revert to the best solution becomes unattainable, even against the wishes of most in the society. Societies must be alerted against, and avoid, voluntarist options that are built as impervious to questioning just because it is so urgent to show action, options that may lead us into wrong paths for too long.

We wandered into this general consideration because the BSwap model requires such a level of cooperation, with so many stakeholders, that there is a real danger that minor barriers might deviate us into paths away from it, and we are convinced that this is a case where public policy may have a central role in coaxing stakeholders into cooperation.

Why public policy is needed: a few issues in the BSwap model

The BSwap model requires the cooperation of a very large number of stakeholders. Public policy may be crucial for coaxing them into treading together a lower cost, faster path towards the transition.

Let us start by listing some of the features of the BSwap model that require some thought:

1. It is not a local initiative; it may start as a regional experiment, but it must be thought of, from the start, as an ambitious continental or universal venture.

2. It is not the venture of a few competing single automakers, but the result of multi-brand,
virtually universal, standards, reached through cooperation. This is the way the model will become efficient and cheap, not by the multiplication of single brand initiatives. Cooperation within the automotive industry, including agreement on standards, is crucial: it may be difficult, possibly an identifiable barrier that must be overcome. Agreement is made more difficult by the convenience that standards for batteries should apply to all vehicles, from the smaller light ones to the heaviest trucks (see Annex 4 for a discussion of this issue of common modular batteries for both light and heavy vehicles, and the next entry of this list).

3. Standards are crucial for success, and they are not limited to the battery itself. They must extend to several systems, such as

a) Batteries: their shape and electric connections must be subject to standards, such that will permit their multi-brand, universal use.

b) Battery extraction and re-insertion into vehicles: vehicles must accept standards such that universal robots in Battery Swapping Stations may service them obeying standardized procedures. (Two distinct standards may be needed, one for single battery mounting, for light vehicles, which may use e.g. one to three batteries, and another for multi-battery racks for heavy vehicles, that may need up to 20 individual batteries, pre-mounted into one or a couple of multi-battery carrier racks, for fast swaps; but of course this is up to industries to decide.)

c) Battery recognition: power and diagnostic systems, including battery management systems, both on-board and in Battery Swapping Stations, must know the characteristics of each battery, so that they can apply the correct strategies for its use (e.g., on-board correct display of state-of-charge and available autonomy, and its efficient use by the electronic power system for traction; and at the BSS, the optimum charging algorithm, and the battery health diagnostics). It may not be sufficient to recognize the type of battery (is it lithium phosphate? or NMC x,y,z? Maybe it is a new sodium ion battery, or...), there are advantages in knowing the parameters of each individual battery, because they will vary along its lifetime, until they do not meet the criteria for quality for that particular type of battery (decided by the battery producer and known by consumers). Data, and forms of communication (for their exchange) between battery and systems, need standards.

d) Power systems, both on-board and in BSSs, must be able to understand the data supplied by each battery, and to adapt internal algorithms to the data parameters. Standards are needed (minimal only, such that the diversity of brand options is not stifled).

e) Quality assurance: chargers at BSSs must classify batteries into three main classes, (i) fit for EV use (sub-divided into sub-classes, such as premium, low-cost, Brand X, ...), (ii) fit for second-life use (most usually within the BSS, for grid and BSS systems support, taking advantage of the internal electric systems and external strong connection to the grid), and (iii) to be sent for repair/recycle. The software and the database for managing battery diagnostics during its charge cycle must be subject to standards, for consumer confidence.

4. Battery Swap Stations are central to the BSwap model, and the model assumes that most will result from an evolution of present fuel service stations. What strategy may be used for bringing
the service station owners into this venture? Who will they be, and what will be their role in
the future? The more general issue: which business models will succeed? Who will order, buy,
and own the batteries? And the chargers and swap equipment? Who will manage the energy
strategy in BSSs? Who will contract the service with vehicle owners?

5. The regulatory framework: As an example, a radical, but perhaps virtuous, approach for BSSs
power management is to hand it over to the grid operator. The manager of the BSS wants so
many batteries charged, and he wants his energy bill to be the lowest; he doesn't want to be
involved in the power management, to follow closely the grid spot needs, and buy and sell along
with the market price signals. The grid operator, on the other hand, would have under his
command a very large amount of flexible demand, and of firm reserve power ready to respond
in milliseconds. Is the regulatory framework amenable to support this win-win situation?

6. Some of the conclusions of this study on the BSwap model are certain to raise a few eyebrows.
A few of them:

a) Future cross-border electric interconnections needs should be revisited in the light of the
new capacity of national systems to balance themselves: most probably, the reinforcement
needs will be reduced compared to those identified in the latest European studies. Present
cross-border electric interconnections are probably sufficient already in many cases, with
no need to reinforce their power capacity, unless justified by commercial energy trade. (The
BSwap model eliminates, or at least reduces dramatically, the need for import/export at
peak times: trade may be spread in time, during the more economically favourable hours,
using lower power capacities.)

b) Public EV chargers will be obsolete within one or two decades. Public investment on such
infrastructures should be reviewed. (Once BSwap takes off, vehicle buyers will massively
prefer BSwap over Plug-in, driven by the inherent ease of vehicle use and lower costs, and
eliminate the need for ever higher density of public chargers.)

c) Public investments in hydrogen and in the gas transport and distribution network should
be reviewed. Hydrogen will not be used for road transport, and many industries will shift
directly from natural gas to electricity, not to hydrogen. The focus for hydrogen should be
chemical (perhaps mostly locally produced, not distributed by an extensive network of
pipelines), and possibly also to power air and maritime transport only.

The list of major stakeholders mentioned is already large, from the automotive, battery, and power
systems industries to the owners of service stations, the grid operators, the regulators, the political
power - not to mention the vehicle owners, and the electricity consumers.

Because of all these special characteristics of the BSwap model, and particularly because of its
capacity to spread its impact into many aspects of how society works and evolves, and of the large
number of stakeholders involved, political powers will be necessarily called upon. Once they accept
that the vision brought by the BSwap model is worth study and proof of concept, public policy may
play a crucial role in coaxing stakeholders into working together and treading a fast, lowest cost, path
towards this disruptive transition \footnote{While taking care not to unduly favour the BSwap model against others, and vice-versa.}. It is easy to detect barriers to this transition, and to guess how
public policy may help smooth them, promoting the most acceptable, least cost, fastest route to the future. We believe this is possible because there are so many win-win situations that cooperation should far outweigh normal competition.

**Possible paths**

*A speculative exercise: what might be the answers to some of the questions, and possible paths for the BSwap transition*

Here we do not attempt to propose public policy, we simply submit a mere reflection exercise, a highly speculative exploration of possibilities and issues, with an eye on how to reach desired outcomes with lowest public investment costs.

1. BSwap is not a local initiative; it may start as a regional experiment, but it should be thought of, from the start, as an ambitious continental or universal venture.

One way to ignite the BSwap venture is to begin locally, say with metropolitan buses and taxis. One advantage is the elimination of atmospheric emissions from such transport services in highly populated areas; one danger is the multiplication of local technical solutions: public policy should intervene and encourage replication of good, standard, scalable solutions.

A second way, more demanding because it immediately raises the core issues of standards, but, on the other hand, already focused on the future, global, BSwap model, is to start with the installation of BSSs along main long-range traffic routes. The initial focus could be on heavy vehicles, for which decarbonization gains are faster: long-range trucks are responsible for a large, and ever increasing, fraction of emissions, and industry is searching for a solution to make heavy goods transport compatible with battery electric traction, without the nightmare of autonomy and charging logistics, and to avoid resorting to much higher cost solutions such as hydrogen or synthetic fuels. This would be the major step to the vision of long-range road transport with as low emission impact as trains, but on rubber wheels (with the advantage of transport with geographical capillarity) and capable of grid service (which trains aren’t).

Ideally, swap robots for light vehicles should be simultaneously offered, a faster jump into the future. One advantage is the discouragement of the complete separation of battery standards for light and heavy vehicles, which should be avoided. This combined solution would use the same modular batteries, shared by light and heavy vehicles; two robots would probably be needed, one for single battery swaps in light vehicles, another for multi-battery racks for heavy vehicles.

2. BSwap is not the sum of ventures of several competing single automakers: cooperation within the automotive industry, including agreement on standards, is crucial; initial cooperative projects should include other future players as early as possible

The best example of cooperation so far comes from the 2-wheel sector: Honda, KTM, Piaggio, and Yamaha signed in 2021 a consortium agreement for swappable batteries. They saw the advantages of multi-brand, shared, swappable batteries over their naturally ingrained competitiveness. The aim of

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155 This was a path tracked by NIO, when in 2019 this automaker company installed its first 8 BSSs along the busy Beijing – Shanghai route.
their consortium clearly states their ambition:\(^{156}\):

a) "**Develop** common technical specifications of the swappable battery systems

b) **Confirm** common usage of the battery systems

c) **Make, and promote**, the Consortium’s common specifications as a standard within European and International standardization bodies

d) **Expand the use of the Consortium’s common specification to global level**

A similar consortium for auto and truck makers has not yet been reached, although it would be most welcome by their clients. Imagine an association of automotive industries spanning several geographies and industries of several continents: think of European, Asian, and American industries with simultaneous experiments on battery swapping\(^ {157}\). However, for the moment, it seems that the barriers of competition and past history\(^ {158}\) have the upper hand.

Policy may of course help industries agree on common standards. A possibility is to coax them with public co-investment policy focusing only on paths with converging industry standards.

Cooperation must not be limited to batteries, as we showed above. There is no doubt that a long road of technical development must be treaded, led by industries, their cooperation coaxed by public co-investment policy.

Because Battery Swap Stations are central to the BSwap model, and the model assumes that most will result from an evolution of present fuel service stations, early involvement of fuel service station owners from the start should be encouraged, because this is preferable to try to find new sites (avoiding the need for licensing, and using existing infrastructures - road accesses, civil construction, grid access, personnel, and services). Starting projects would benefit from lowest investment and be on the right track for the least cost future.

In the far future, service stations will be high power electric energy hubs, on one hand, and mobility service providers on the other. They may well be prize assets for electric utilities, or grid operators, but these may find it better to take over the energy management side only (grid connection, local generation, ...) and leave to others the battery and infrastructure management, and service to mobility.

Note that in the near future, while the grid is still not decarbonized and is *e.g.* reliant on natural gas for balance, the model for battery and energy management will be different from that in the future, mature BSwap model:

a) In the near future, grid balancing services may not be the primary focus, because for the moment grids are stabilized by other means; so, costs are minimized by relatively rapid

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\(^ {156}\) Copied from their statement after the constitution of the consortium.

\(^ {157}\) Including *e.g.* companies with battery swapping experience (such as NIO, Renault, and Tesla, to cite one from each continent), and companies which have gained know-how on electric traction and are willing to join the experiment (from our perspective, companies such as Daimler, which are relevant industrial players both in the light and heavy vehicle segments, would be especially welcome).

\(^ {158}\) As an example of how history weighs in, in 2013 Tesla and Elon Musk announced battery swapping as the future of electric vehicle industry, but when the experiment failed a few years after (wrong time, insufficient EV density, wrong model, single brand), they retreated into investing in ever faster charging of ever more chassis-integrated batteries and continued to focus on proclaiming their unique battery quality as a commercial weapon. How might Tesla by-pass its entrenched position? Maybe just like the motorcycle industries, by starting with one special model, conceived to participate in the battery-swap experiment?
rotation of batteries: instead of the 24h residence time, residence time may be much smaller: with slow charging down to 3,3 hours, the number of extra batteries and the number of chargers is smaller than in the mature BSwap model. Initial investment costs are lowered by less batteries and less chargers than in the model developed above for a more distant future, although some energy management would already lower energy cost.

b) In the longer run, as the grid decarbonizes and needs balancing services, and as batteries and chargers become less expensive (and as more second-life batteries become available), then the energy and battery management will mature into longer residence times, and higher grid balancing services to the grid, with the higher equipment and extra battery costs being more than compensated by the diminishing cost of electric energy.

3. A general issue: which business models will succeed? Who will order, buy, and own the batteries? And the chargers and swap equipment? Who will contract the service with vehicle owners?

We dare not answer this question, because industry and investors are certainly more competent in designing business models than us. We just venture suggesting the easiest answer: automotive and battery industry joint ventures. They will design and order batteries for their vehicles (possibly branded, but subject to standards), contract the “battery as a service” service with their clients, who choose one of the commercial contracts available, offered by the vehicle seller (with support by the automaker joint venture, but with enough freedom for commercial competition).

They may also order, buy, and own the battery charger racks and the BSwap robots, or even own BSSs, but this is not necessary or evident: as long as there are standards, these infrastructures may also be the property of a BSS owner, or of specialized technical companies. Or even of energy utilities.

Conclusions

The aim of this chapter is not to propose concrete public policy, but rather to raise the issues and simply point out some ideas and possible paths that we hope industries and institutions around the world will consider and eventually result in proposals of projects and policies that may start the road to a promising future.

GUIDELINES FOR PUBLIC POLICY

We list a few general recommendations for public policy that may promote a favourable path to a decarbonized future and avoid unnecessary meanders and dead-end paths.

Our study suggests some controversial guidelines for future investment needs.

On storage

The BSwap model for road transport will strongly mitigate the need for large-scale energy storage by other means, a consequence of

• turning road transport demand into a flexible load, complemented by
• battery storage at the BSSs (probably supported by second-life batteries, using the available grid connections and the continuous supply of batteries which no long satisfy quality criteria for transport).
Policies on the future needs for energy storage should therefore be reviewed in this light. However, BSSs alone aren't sufficient for supply security, they simply decrease the need for further storage, which is still needed, especially for long periods of low wind and solar generation.

**The Portuguese example**

The concrete example of the Portuguese national system, our case study, produced interesting results on the future needs for energy storage. The main conclusion:

There is no need for any large-scale energy storage beyond

1. The already planned and mostly executed hydro pumped storage (with just a recommendation of some additional, low power, pumping capacity in large existing reservoirs presently with no planned pumping installations, with the aim of achieving a more permanent strategic energetic, economic, and ecologic, water reserve), and
2. The intrinsic storage of the battery swapping stations (which complements their most effective impact on the electric system by acting as a large-scale, fully flexible, demand).

Hydro power (with its intrinsic flexible generation, complemented by the demand flexibility of pumping) together with the battery swapping stations (with their intrinsic flexible demand, complemented by the flexibility of their battery-to-grid generation capacity) satisfy the conditions for a balanced electric system, with no need for any further large-scale storage.

The high-power flexible demand of battery swapping stations easily absorbs the solar (or wind) generation peaks, even with a solar photovoltaic fraction reaching about 45% of all electricity generation: there is no need to install any further storage capacity to store solar (or wind) power so it can be used later.

This large-scale demand for peak solar (or wind) generation due to BSSs guarantees that solar and wind power are not massively curtailed or sold at nearly zero prices. This is one of the contributions for an important outcome of the BSwap model: the price of electricity for general consumers is lowest.

**Other regional systems**

Our Portuguese case study highlighted and quantified the further need for energy storage, and demonstrated how this need was satisfied by the national plan for hydro pumped storage.

Hydro pumped storage is arguably the best mature energy storage technology, boasting high round-trip efficiencies (82% with state-of-the-art reversible pumps), and long-term, high-capacity, storage, at relatively low costs. In regions where available, it is an ideal complement for the short term, high power, flexible load plus storage of BSSs.

In regions where hydro pumped storage is not practical, one has to study the best balance of

1. Other physical storage means (*e.g.* compressed air in large caves, where available)
2. Chemical storage
   
   a) in batteries (which would ideally be placed in BSSs, to take advantage of the existing infrastructure),
   b) in the form of a decarbonized fuel (*e.g.* hydrogen), or natural gas (the cheaper, but non-decarbonized, solution), to be burned in the old turbines for power. (Note that natural gas
may be a good solution, if it is used as a reserve power source to satisfy only a few percent of annual generation needs: decarbonization of the electric system by >90% is not optimum on emissions, but probably a good balance for cost and security of supply.)

3. Long-distance power connections.

**On long-distance power connections**

The Portuguese case study demonstrated how the BSwap model drastically reduced the need for long-distance, cross-border, power connections: BSSs were able to absorb the generation peaks, and to attenuate the need to import/export for balance down to the order of 1% of generation only. This does not mean that long-distance connections are unnecessary, but rather that they must be justified by commercial energy traffic and security of supply. In this case, note that the BSwap model allows spreading in time e.g. solar energy export away from its natural peaks; one consequence is the increase in value of the exported energy, but another is the higher efficiency of use of transport lines, which would require far lower capacity than if they were exporting the raw solar or wind generation.

Therefore,

- We should review the power capacities of cross-border country interconnections. They might be lower than presently foreseen.

**On hydrogen**

We should also review the policies on hydrogen.

One reason for this is that battery swapping will be at least twice as energy efficient as hydrogen in the future (presently, an even higher factor) when the final energy is electricity, and this is the main reason why the BSwap model results in far lower prices for transport and electricity than the Hydrogen model.

Therefore, investment in green hydrogen should focus only on the future applications where it might be competitive:

1. In transport:
   - Certainly not for road transport (due to its high over-cost against BSwap)
   - Probably yes in air and maritime transport (although possibly not as hydrogen gas, but rather in the form of a transformed molecule, possibly a synthetic or hybrid liquid fuel)

2. As a general energy vector:
   - Hydrogen, as an energy vector, will almost always lose, in the future, against competition with electricity, wherever it can be used, from buildings to industry. (The great exception is air and maritime transport.)
   - The power-to-gas concept is not ruled out entirely, but only because it might allow some more immediate decarbonization, even if at a high cost (the efficiency problem is not as severe as cited above, when the final energy is heat, rather than electricity). But we expect the power-to-gas concept to play at most a bridging role, as discussed above, which will become mostly obsolete as industries adapt to the lower-cost electric solution. The cost/benefit of the power-
to-gas concept must be very closely scrutinized, keeping in mind that it is a transitional model, and that it might produce the perverse consequence of industry obsolescence (by maintenance of present gas burning processes, and discouraging early evolution towards electric power).

3. As a molecule:

- Hydrogen has probably a bright future as a chemical. Examples range from the steel industry (where hydrogen might be the iron ore reducing molecule), to fertilizers, synthetic fuels (for air and maritime transport), ... While it will not be cheap, it may well be proven competitive against other paths for decarbonization. We therefore welcome prudent investment in such technologies and in pilot projects, but not in high-risk massive investment in large-scale projects with unproved competitiveness.
VIII • THE CHOICE

We have detailed the issues of simultaneous decarbonization of the power and road transport systems, proposed different solutions, and compared their outcomes. We frequently used a provocative style, perhaps even proselytizing or edging on triumphalism, the intention being to provoke in the reader a vivid reaction, and a rethinking of ingrained visions of the future with inclusion of the unusual propositions we present here. To the readers whom we may have displeased with this option, our apologies.

We finally wrap up our message, keeping true to the chosen style.

Rigid and flexible demand

Consider domestic illumination. You and I turn on and off lamps when we want. Now add these millions of individual decisions, and the result is a statistical electric energy demand profile, forecastable and rigid: it does not adapt to higher or lower power availability in the electric system. The system must adapt to demand, for instance feeding more water into the turbines of a hydropower station, or more gas into the burners of a thermopower plant, when more lamps are turned on.

In a future electric system, particularly if dominated by non-dispatchable generation such as solar and wind, balance is a central problem. For every sector of consumption, we must always ask how much it costs to make generation and consumption meet.

A rigid demand profile cannot adapt to the constant generation of nuclear power, or to the vagaries of solar and wind generation, so the system must adapt, for instance using means of storing energy produced at time X to be released and consumed at time Y. Now any storage system will have costs, due to

1. The round-trip efficiency being always less than 100% (it might be relatively high, about 80%, in the case of hydro pumping, or as low as 50%, in the case of storage by hydrogen): some energy is always lost and must be paid for; and
2. Investment and operational costs of the storage system.

Suppose now that the electric energy consumption of a given relevant sector might be rigid (with no regard to grid condition) or become flexible (adjustable to grid condition: maximum demand in times of abundant power, minimum at times of scarcity). While each case must be studied individually (namely considering the profile of the rigid consumption, and the feasibility and costs of making it flexible), it is easy to guess that, in general, the costs of a flexible load are much lower than those of a rigid load.

In fact, the effect of a flexible load on the electric system can be approximately reproduced by (i) the...
(original) rigid load, plus (ii) a storage system, with its inefficiency and cost issues\textsuperscript{159}. On the contrary, flexible demand may well boast 100\% efficiency, and the investment and operational costs may be very low (for instance, just an upgrade in power connection and in internal power management).

**The first choice for road transport: should demand be rigid, or flexible?**

Consider now the road transport sector, which will be responsible for a very relevant fraction of future electric energy demand.

If we extend the present system of plugging electric vehicles to a grid-connected socket for charging, the millions of individual actions will result in a statistical rigid demand profile. Some adaptation to the grid condition is possible\textsuperscript{160}, but this modest flexibilization does not change the essentially rigid nature of Plug-in demand.

The alternative is to give up the chaotic, individual decisions, and turn to a coherent, centralized way of powering road mobility that turns its demand into a flexible load. This opens the possibility of lower costs for a balanced electric system and is therefore a tempting choice. Furthermore, due to the decoupling of vehicle utilization from energy procurement from the grid, you realize that refuelling may take only a minute, and that vehicle use, including the heaviest trucks, may become as easy as today.

**The second choice for road transport: hydrogen or battery swapping?**

The two possibilities for turning road transport demand into a flexible load are hydrogen or battery swapping. The choice is yours:

- Do you want an irreversible\textsuperscript{161}, intrinsically low efficiency, high-cost process? Then choose hydrogen.
- Do you want a reversible, intrinsically high efficiency, low-cost process? Then choose battery swapping.

We hope the reader feels armed enough, with the arguments we put forward in this essay, to make his choice.

\textsuperscript{159}This is somewhat parallel to the reverse problem of flexible generation. Imagine a dammed water reservoir fed by a river. You could just use all the incoming water for hydropower generation, and then use a reversible pumping system to adjust net production to system needs; however, it would always be cheaper and far more efficient to start by simply retaining the water in the reservoir at times of power abundance in the grid, and to feed it to the turbine in times of deficit: no investment in a pumping system, and no inefficiency losses.

\textsuperscript{160}Some adaptation is in fact mandatory: suppose that, when people come home in the evening and switch on several home appliances (for heating, cooking, lighting, communications, ...), they also plug their electric cars to a home charger. It is easy to guess that the present peak consumption of winter evenings, when power consumption beats annual records, would grow to impossible heights. Some management of home chargers will be mandatory.

\textsuperscript{161}Irreversible, firstly, in the thermodynamic sense. The present hydrogen cycle is intrinsically irreversible: even theoretically, the cycle cannot approach 100\% efficiency. Secondly, it is irreversible also in practical devices: an electrolyser does not use hydrogen and oxygen to produce electric energy, and a fuel cell is not designed to use electric energy to produce hydrogen. Both devices work in one direction only, and so the use of hydrogen as storage implies “double” investment, in separate facilities for (i) hydrogen production and for (ii) electric generation from hydrogen. On the contrary, a Li-ion battery is essentially reversible: all you have to do is change the direction of the electric current, and recover, even in practice, close to 100\% of the energy. This simple (thermodynamic and practical) reversibility offers a bonus, beyond demand flexibility: it is inexpensive to turn a battery charging system into a grid supporting firm-power reserve.
Conclusion

In this essay we have tried

- To point out the main issues of the future, decarbonized, road transport and power systems, and
- To analyse alternative solutions, and estimate their outcomes, in rough, simplified, but quantitative calculations.
- The result of comparing the outcomes of the different model solutions became a clear demonstration of the superiority of one of the options, battery swapping.

We showed why battery swapping is the best option for the transition to decarbonized road and power systems, and how the outcomes of this model for road transport spill onto many other human activities.

We hope we convinced the reader that it is urgent to reassess the plans that have been proposed so far, with a rational and critical eye, and with inclusion of this understudied, overlooked, and possibly most promising of the paths that will lead us into the future.
ANNEX 1: LITHIUM-ION BATTERIES

Li ion batteries are a fascinating breakthrough\(^{162}\), and are presently ubiquitous in electric vehicles. Although much research is being carried out in other promising families of batteries, it is likely that the Li-ion family will play the major role in the next decades. It is therefore worthwhile looking into how they work.

Lithium is the lightest element of the sodium and potassium family, the alkali metals, which readily lose their external electron to form very stable, single charge, positive ions. Li\(^+\) is tiny\(^{163}\), and so can easily penetrate solid structures.

Solids such as graphite, silicon, or silicon carbide, can take in large concentrations\(^ {164}\) of Li\(^+\), but require that the ions be forcefully pushed in: Li\(^+\) ions within such materials are in a high state of energy.

A completely different family of solids, typically mixed metallic oxides, or phosphates (at least one of the metallic elements being a transition metal), such as NMC (nickel-manganese-cobalt oxide), or LFP (lithium iron phosphate), also take in readily large concentrations of Li\(^+\). However, rather than requiring that Li\(^+\) ions be pushed in, they strongly suck in the available ions. Li\(^+\) within such materials is in a low energy state.

A Li-ion battery is made of two electrodes, say one made of graphite and the other made of NMC, separated by an electrolyte, a (liquid or solid) medium where Li\(^+\) ions move freely, but not electrons. In a low charge battery, most Li\(^+\) ions will be within NMC, and very few in the graphite electrode. The battery is charged by forcing Li\(^+\) ions to leave the NMC electrode and pushing them into the graphite electrode by applying an electric potential difference sufficient for an electric current, due to the motion of Li\(^+\) ions\(^ {165}\) across the electrolyte, to flow. This potential is an effective measure of the difference between the two states of energy of Li\(^+\) in each of the electrodes and is typically >3 V: in the cited example of a graphite/NMC cell, the average equilibrium voltage is usually cited as 3.6 V\(^ {166}\).

The charged battery can be used as a source of electrical power in an external circuit: for every Li\(^+\) ion flowing inside the battery from graphite to NMC, the ion energy difference is available for one electron to flow and produce work in the external circuit from the graphite to the NMC electrode.

To me, the most striking fact about Li\(^+\) batteries is their intrinsic simplicity: Li\(^+\) ions simply move between high energy states (in a graphite family electrode) and low energy states (in an oxide family electrode). No other reactions are needed\(^ {167}\).

Let us review some of the properties of Li\(^+\) batteries that are relevant for electrified mobility:

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162 The Nobel Prize in Chemistry 2019 was awarded to John B. Goodenough, M. Stanley Whittingham, and Akira Yoshino for their contributions to the development of the lithium-ion battery.

163 Ionic radius of Li\(^+\) is only 76pm.

164 Graphite, presently the most used anode material, should allow intercalation, between its graphene structural sheets, up to 1 Li\(^+\) / 6 carbon atoms, or, in more practical units for batteries, 32Ah.kg\(^{-1}\). However, capacities of 1200 Ah.kg\(^{-1}\) have already been demonstrated in SiC\(_x\), and Si has a theoretical specific capacity over 3500Ah.kg\(^{-1}\), almost 10x that of graphite. This hints at possible means to increase the energy density of Li\(^+\) batteries.

165 They may move as single ions, or loosely bound to a carrier molecule.

166 This means that the energy difference of a Li\(^+\) ion in NMC versus in graphite is ≈3.6 eV, or 350 kJ per mole of Li\(^+\). Or, more practically, that such a battery containing 7kg of lithium, available for transit between electrodes, would have an energy content of 96 kWh when fully charged.

167 In fact, Li\(^+\) cells are designed to avoid unwanted side reactions that may degrade them.
**Round-trip efficiency**

Round-trip efficiency is defined as the ratio between the electric energy that a battery gives out while discharging, and that which was spent while charging. Any irreversibility in the cycle will cause this energy efficiency to drop below 100%.

Li+ cells are excellent in this respect: efficiencies of ≈99% are easy to demonstrate in a slow charge/discharge cycle but may decrease to ≈85% for very high rates.

In a fast cycle, with high currents, efficiency diminishes, mostly due to the ‘internal resistance’ of the cell. One reason is that for ions to move faster in the electrolyte, you must push them, and so loose some energy as Joule heat. Other regions where energy may be lost are the electrode surfaces and their bulk (which ions must transpose and then diffuse), and their connection to the metallic conductor. Since electric vehicles use battery packs, made of many individual cells, some ohmic losses will also occur in their interconnections. How serious all these losses are, in present EV batteries, depends on design and manufacture, and for recent batteries only orders of magnitude can be obtained from the EV companies. Typically, the efficiency of a battery itself ranges from >95% for slow charging to ≈85% in very fast charging. However, the power electronics for charging (grid to battery) and discharging (battery to motor) add their own losses to the total system, so that for mixed slow and fast charging, in regular use of a vehicle, efficiencies of the order of 80% are cited, and will be used in this work for the Plug-in charging model of transport. On the other hand, if charging is limited to low rates, the round-trip efficiency will be higher, say 87%, the value used here for the Battery Swapping model of transport.

**Degradation**

A crucial characteristic of a battery is its lifetime, the number of years a battery may be used satisfyingly for transport. This depends on how it is used, since the main cause of degradation is how often some deleterious procedures are carried out. For instance, fast charging is always deleterious, but at high or very low ambient temperatures it may be fatal. Fast charging is also worse if applied to reach a high state of charge. In general, battery lifetime can be vastly improved by

- avoiding fast charging entirely, and especially in uncontrolled extreme ambient temperatures.
- avoiding charging to, and long permanence periods at, a high state of charge.

In the normal use of a plug-in vehicle, fast charging is unavoidable in long range travel, or in a commercial or shared vehicle in high rate of use. Also, fast charging at high ambient temperatures, for instance, may be unavoidable. And range anxiety leads electric vehicle owners to keep the battery fully charged.

On the contrary, in the Battery Swap model, all battery charging is performed at slow rates, and in

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168 'Slow' or 'fast' rates of charge/discharge are imprecise terms, of course. As an order of magnitude rule, 'fast' is usually applied to rates that would totally charge/discharge a battery to/from its nominal capacity in ≤1.5 hours, and 'slow' in ≥3.5 hours.

169 A recent review, citing several results: A review on the key issues of the lithium ion battery degradation among the whole life cycle, Xuebing Han et al., eTransportation · August 2019, doi.org/10.1016/j.etran.2019.100005.

170 Some mechanisms are well known, and all modern packs have a Battery Management System that avoids, e.g., overcharge or too deep discharge, which are fatal for battery health. Degradation is also a function of calendar time, although usually not dominant; it is highest for a fully charged battery.
a controlled temperature environment. Furthermore, since range anxiety ceases to exist, batteries for swapping may be most of the times charged only to, say, 85%; fully charged ones may be asked for, but usually for immediate use in travel.

We therefore expect that in the BSwap model batteries will have a significantly longer lifetime than within the Plug-in model. In this work, conservatively, we assume a lifetime of 8 years for Plug-in, and only a modest increase to 9 years in BSwap.

Cost and technology evolution on Li ion batteries for electric vehicles

The cost of Li ion batteries per nominal capacity has come down precipitously from over 1.100 $/kWh in 2010 to 137 $/kWh in 2020. Battery packs for electric vehicles in 2020 cost \(\text{weighted average} 126$/kWh; at the cell level, the average cost was already 100 $/kWh. The rate of decrease has been consistent over the years; in the two years 2019-2020, costs have fallen by 13%/year. However, materials availability and cost issues have recently stopped this trend. This was expected, as it always occurs in fast growth industries with maturing technology and supply chain, and we may be reassured that these growth pains will be solved in the future, just as happened in many other industries\(^{172}\).

Vehicle manufacturers compete in the offer of battery packs with improved technology, higher capacity (which translates into higher autonomy range) and lower price. One example: Tesla has announced its new high energy density packs, to begin production in the near future, at 380 Wh/kg, a step ahead from present production of 260 Wh/kg packs. Another example: NIO, which has a 100 kWh pack in production, selling for 88 $/kWh (already below the old Grail of 100 $/kWh), announced in 2021 its new 150 kWh pack, all solid state (no longer a liquid electrolyte), with anode including silicon carbide, with a nominal energy density of 360Wh/kg. NIO is a particularly interesting example, in that it is the fourth upgrade in battery technology and improved capacity in the last few years, but all the new packs can be retrofitted into older vehicles: the battery packs are all compatible. It is no coincidence that NIO offers Battery as a Service, with battery swapping facilities. Compatibility is key to customer satisfaction: the owners of older NIO vehicles can enjoy the benefits of battery technology evolution, with successive upgrades of the range of their old cars.

We may be certain that industry will find a way to produce better, cheaper batteries, whatever the technology evolution, even away from lithium.


\(^{172}\) One example: the rapid expansion of the solar photovoltaic industry in 2008 led to prices for solar silicon, its basic material, to hit 500 $/kg in the spot market, while production costs are below 15 $/kg.
ANNEX 2: HYDROGEN FUEL CELLS

A hydrogen fuel cell uses the energy released when combining hydrogen with oxygen into water to produce electric energy. However, this reaction is not spontaneous: the reader may remember, from the chemistry labs in school, how a spark or a flame was necessary to start the combination of H₂ with O₂. The reason for this is that some energy must be spent to split the H₂ and O₂ molecules into H⁺ and O₂⁻ ions before they can recombine into H₂O and release energy.¹⁷³

The same is required within a practical fuel cell. A typical fuel cell is composed of two porous electrodes and a membrane between them which allows H⁺ ions to pass through it. H₂ gas is fed through one of the electrodes where it dissociates into positive H⁺ ions. This process requires some energy because the H-H bond is strong. The H⁺ ions move, through the separating membrane, to the opposite electrode, where they react with oxygen ions to form water. For these oxygen ions to form and react with hydrogen ions, the strong O=O bond must also be broken, and this also requires energy. Unfortunately, the rate at which these reactions proceed depends on how much additional external energy is provided. To go faster, we need to apply more. In short, the need to apply additional external energy to get the reaction going is a significant loss mechanism (even with the indispensable use of a catalyst, presently platinum), which reduces practical fuel cells efficiencies by 10 to 20%. A second significant loss mechanism is the ohmic loss due to the transport of H⁺ ions from one electrode to the other (another 10 to 20%): H⁺ ions must be pushed to move at an acceptable speed through the membrane. These two loss mechanisms are the focus of much research which attempts to reduce these losses with the development of cost-effective materials. Finally, there is an unsurmountable loss mechanism (17%) dictated by thermodynamics. All energy conversion devices are “hamstrung” by this fundamental limit set by nature on all irreversible processes. The combination of these loss mechanisms, in a practical commercial device, results in typical fuel cell efficiencies between 50 and 60%.

A practical fuel cell has the great advantage of continuous feed of reactants, which may be stored, with an exhaust which is simply water. It also has several disadvantages:

- Low efficiency: present state-of-the-art cells may achieve average efficiencies of the order of 60%. Higher efficiencies are demonstrated, but at a given power regime; it is difficult to improve overall efficiency in the varying power demand typical of driving a vehicle: present average efficiencies of ~50% are normal.
- Cost: fuel cells are not simple devices and use high-cost materials such as platinum. Their limited lifetime increases depreciation and substitution costs.
- Non-reversible: contrary to a Li-ion battery, a fuel cell works in one direction only.¹⁷⁴ The

¹⁷³ The H-H and O=O bonds are so strong that ¾ of the energy of H-O bonds in water is used to break them; only ¼ is available in the end, minus all the energy losses necessary for the reaction to occur at an acceptable rate. For simplicity in this description, we are not considering any other intermediate states, only molecules and atomic ions, and only H⁺ ion fuel cells.

¹⁷⁴ All fuel cells are irreversible in the thermodynamic sense. Reversible hydrogen fuel cells are not theoretically forbidden, but all practical cells in existence are irreversible. A second meaning of reversibility is the possibility of turning a fuel cell into an electrolyser cell, capable of producing electric power while consuming hydrogen gas, and of producing hydrogen while consuming electric power. Such devices are by no means forbidden to exist, although their cycle will be thermodynamically irreversible, and therefore pay an inefficiency price, but might find applications, taking advantage of their closed cycle, and of possibly lower investment cost than separate devices to perform each of the functions. To our knowledge, there are no such practical devices in production.
reverse reaction, electrolysis, must be performed in a different equipment, an electrolyser. A consequence of this is a longer process chain and higher investment needs than in the case of Li-ion batteries.

If we are to use hydrogen as a decarbonized energy vector, e.g. in transport, then round-trip efficiency, defined as the ratio of (i) the electric energy that reaches the electric motor (produced by an on-board fuel cell), and (ii) the electric energy that was used to produce hydrogen from water electrolysis and feed it to the fuel cell (the energy used for compression, distribution and dispensing is also relevant) dictates how much generation is needed to power electric traction.

Unfortunately, state-of-the-art round-trip efficiencies are very low, because they combine several inefficiencies along the path. In the use of hydrogen for road transport, grid-to-on board electric motor efficiency is presently below 30%\textsuperscript{175}. This should be compared with round trip efficiencies reaching 90% for Li ion batteries, which are reversible devices\textsuperscript{176}, with internal efficiencies close to 100%, and a conceptually very simple process chain.

Of course, there is plenty of room for improvement of the hydrogen cycle efficiencies, the starting point being so low. However, unless a series of combined disruptive technologies comes up, it will be challenging to achieve round-trip efficiencies for road transport of the order of 50% in the next decades.

In this work, we use for road transport an overall round-trip efficiency of 37% (a significant improvement from present practical status; for instance, we assume average fuel-cell efficiencies of 62% for a light passenger vehicle, and 65% for a heavy truck) for the interim calculations, by the mid 2030’s. When discussing the impact of H2 transport on the electric system in 2050, we assume that a much higher round-trip efficiency of 50% has been achieved by then.

\textsuperscript{175} Hydrogen powered fuel cell electric vehicles are frequently cited as being more energy efficient than their diesel ICE counterparts. While this is usually true (even if only marginally because diesel motors in trucks have also been improving their efficiency) if you consider only tank-to-wheel efficiency, once you consider the full hydrogen cycle, H2 vehicles are actually less energy efficient than diesel powered ones.

\textsuperscript{176} Li ion batteries are nearly thermodynamically reversible, which is why a charge/discharge cycle may approach 100% efficiency. It is also reversible in the more ordinary sense, because all it takes is to change the electric current direction to turn a battery from an energy store into a source of power.
ANNEX 3: PARAMETERS FOR ROAD TRANSPORT MODELS: ICE, H2, PLUG-IN, AND BSwap

Definition of the 4 models (ICE, H2, Plug-in, BSwap) from the perspective of a truck owner.

### Common truck characteristics
- **Load**: 40 ton tractor
- **Distance travelled / year (average)**: 120,000 km

### Basic vehicle Cost
(without power systems: motors, transmission, fuel cells, tank, batteries, power management,...)
- **50,000 €**

### Energy supply cost (Fuel distribution, Grid)
- **Electric energy, low rate** (applies to H2 and BSwap models)
  - **40 €/MWh**
- **Electric energy, normal rate** (applies to Plug-in model, heavy EVs)
  - **100 to 150 €/MWh**
- **Diesel fuel (applies to ICE model)**
  - **1,300 €/l**
- **Diesel fuel (applies to ICE model)**
  - **0,650 €/l**
- **Battery cost**: 70 €/kWh

### Cost of energy module
- **ICE**: 65,000 €
- **H2**: 64,131 €
- **Plug-in**: 45,000 €
- **BSwap**: 45,000 €

### Average fuel consumption
- **ICE**: 21.58 l/100km
- **H2**: 5.47 kg H2/100
- **Plug-in**: 1,160 kWh/km
- **BSwap**: 1,160 kWh/km

### Truck repair & maintenance cost
- **ICE**: 12,500 €/year
- **H2**: 9,400 €/year
- **Plug-in**: 6,250 €/year
- **BSwap**: 6,250 €/truck.year

### Capital cost
- **Constant payments** (for capital and interest)
  - **6 %**
  - at an annual rate of

### Finantial: Depreciation years
- **Truck**: 8 years
- **Batteries (H2 and plug-in model)**: 8 years
- **Batteries (BSwap model)**: 9 years
- **Fuel cells, H2 tank**: 8 years
- **Fixed installations**: 15 years

### Financial

### Batteries (H2 tank)
- **100 kWh**

### Battery average lifetime
- **ICE**: 8 years
- **H2**: 8 years
- **Plug-in**: 8 years
- **BSwap**: 9 years

### Battery capacity per module
- **ICE**: 1,000 kWh
- **H2**: 1,000 kWh
- **Plug-in**: 1,000 kWh
- **BSwap**: 1,000 kWh

### Battery average lifetime
- **ICE**: 8 years
- **H2**: 8 years
- **Plug-in**: 8 years
- **BSwap**: 9 years

### Battery market evolution
- **ICE**: growth/year 6 %
- **H2**: growth/year 6 %
- **Plug-in**: growth/year 6 %
- **BSwap**: growth/year 6 %

### Battery cost evolution
- **ICE**: decrease/year 1 %
- **H2**: decrease/year 1 %
- **Plug-in**: decrease/year 1 %
- **BSwap**: decrease/year 1 %

### Repair & maintenance cost
- **ICE**: 12,500 €/year
- **H2**: 9,400 €/year
- **Plug-in**: 6,250 €/year
- **BSwap**: 6,250 €/truck.year

### Table A3.1
Model parameters for a 40 ton truck (tractor)
Definition of the 4 models (ICE, H2, Plug-in, BSwap) from the perspective of a light passenger vehicle owner.

<table>
<thead>
<tr>
<th>Common characteristics:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>1,0 ton light vehicle</td>
</tr>
<tr>
<td>Distance travelled / year (average)</td>
<td>10 000 km</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Basic vehicle Cost</th>
<th>14 000 €</th>
</tr>
</thead>
<tbody>
<tr>
<td>(without power systems: motors, transmission, fuel cells, tank, batteries, power management systems,...)</td>
<td></td>
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<table>
<thead>
<tr>
<th>Energy supply cost (Fuel distrib., Grid)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric energy, low rate (applies to H2 and BSwap models)</td>
<td>40 €/MWh</td>
</tr>
<tr>
<td>Electric energy, normal rate (applies to Plug-in model) for light EVs</td>
<td>150 €/MWh</td>
</tr>
<tr>
<td>Diesel fuel (applies to ICE model) price (including special taxes)</td>
<td>1,300 €/l</td>
</tr>
<tr>
<td>Diesel fuel (applies to ICE model) price (excluding special taxes)</td>
<td>0,650 €/l</td>
</tr>
<tr>
<td>Battery cost</td>
<td>70 €/kWh</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Financial:</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Capital cost</td>
<td></td>
</tr>
<tr>
<td>Constant payments (for capital and interest) at an annual rate of 6 %</td>
<td></td>
</tr>
<tr>
<td>Financial: Depreciation years</td>
<td></td>
</tr>
<tr>
<td>Truck</td>
<td>8 years</td>
</tr>
<tr>
<td>Batteries (H2 and plug-in model)</td>
<td>8 years</td>
</tr>
<tr>
<td>Batteries (BSwap model)</td>
<td>9 years</td>
</tr>
<tr>
<td>Fuel cells, H2 tank</td>
<td>8 years</td>
</tr>
<tr>
<td>Fixed installations</td>
<td>15 years</td>
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</table>

<table>
<thead>
<tr>
<th>ICE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of energy module (motor, transmission,...)</td>
<td>8 000 €</td>
</tr>
<tr>
<td>Average fuel consumption</td>
<td>4,1/100 km</td>
</tr>
<tr>
<td>Repair &amp; maintenance cost</td>
<td>1 000 €/year</td>
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</table>

<table>
<thead>
<tr>
<th>H2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of energy module, batteries excluded (electric motors, power electronics, fuel cells, H2 tank,...)</td>
<td>9 423 €</td>
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<tr>
<td>Battery capacity</td>
<td>10 kWh</td>
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<tr>
<td>Average fuel consumption</td>
<td>0,80 kg H2/100km</td>
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<tr>
<td>Electrolyser efficiency</td>
<td>76 %</td>
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<tr>
<td>Fuel cell efficiency</td>
<td>62 %</td>
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<tr>
<td>Production, storage, distribution, compression, dispense (capital &amp; O&amp;M costs)</td>
<td>3.5 €/kg of H2</td>
</tr>
<tr>
<td>Repair &amp; maintenance cost</td>
<td>750 €/year</td>
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</table>

<table>
<thead>
<tr>
<th>Plug-in</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of energy module, batteries excluded (electric motors, power electronics,...)</td>
<td>4 000 €</td>
</tr>
<tr>
<td>Battery capacity</td>
<td>100 kWh</td>
</tr>
<tr>
<td>Average consumption</td>
<td>0,162 kWh/km</td>
</tr>
<tr>
<td>Battery average lifetime</td>
<td>8 years</td>
</tr>
<tr>
<td>Battery average round trip efficiency</td>
<td>80 %</td>
</tr>
<tr>
<td>Average cost of grid energy</td>
<td>150 €/MWh</td>
</tr>
<tr>
<td>Cost of plug-in chargers</td>
<td>83 €/MWh</td>
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<tr>
<td>Repair &amp; Maintenance cost</td>
<td>500 €/year</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BSwap</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of energy module, batteries excluded (electric motors, power electronics,...)</td>
<td>4 000 €</td>
</tr>
<tr>
<td>Battery capacity on-board</td>
<td>100 kWh</td>
</tr>
<tr>
<td>Average consumption</td>
<td>0,162 kWh/km</td>
</tr>
<tr>
<td>Average cost of grid energy</td>
<td>40 €/MWh</td>
</tr>
<tr>
<td>Battery average lifetime</td>
<td>9 years</td>
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<tr>
<td>Battery module capacity</td>
<td>50 kWh</td>
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<tr>
<td>Battery average residence time at BSS</td>
<td>24 hours</td>
</tr>
<tr>
<td>Battery round trip efficiency, average</td>
<td>87 %</td>
</tr>
<tr>
<td>Battery market capacity evolution: growth/year</td>
<td>6 %</td>
</tr>
<tr>
<td>Battery cost evolution: decrease per year</td>
<td>1 %</td>
</tr>
<tr>
<td>Repair &amp; maintenance cost</td>
<td>500 €/year</td>
</tr>
</tbody>
</table>

| TABLE A3.2 | Model parameters for a light passenger vehicle |
ANNEX 4: WHY **BSwap** BATTERIES FOR LIGHT AND HEAVY VEHICLES SHOULD BE COMPATIBLE

*Modular batteries, compatible for all vehicles for road transport, light or heavy, is the best choice.*

It is not a model requirement that batteries for light and heavy vehicles be interchangeable, and industry will probably be tempted into different standards, given the relative separation of the industrial segments. What would be the consequences?

**Battery rotation and lifetime**

Heavy electric vehicle (HEV) batteries would be subjected to many more cycles per year than those for light electric vehicles (LEV). Assume a HEV that travels 100,000km/year and a LEV that averages only 10,000km/year. If their autonomy is similar, then HEV batteries will be cycled 10x more per year than those for the LEV. If we assume, say, 600 cycles as an average lifetime for a battery fit for transport, then a HEV battery might last only 4 years, while a LEV battery would in theory last 40 years, which of course will not happen, as with such time scales their lifetime will be limited by calendar time, not by cycling. Now, if calendar lifetime becomes dominant for most batteries (those on-board LEVs), this means a blatant misuse of resources, both materials and capital. Also, LEV owners would benefit very little from the technical improvement of batteries because of their extended lifetime, contrary to the case of HEV, whose batteries would be rapidly substituted by new technological generations.

If HEV and LEV batteries were interchangeable, an intermediate virtuous lifetime would be the consequence. The outcomes would be a more efficient use of materials and better access to new battery technologies for all, and lower global costs.

**Standards**

The other issue is standards.

Modular batteries of, say, 40 kWh capacity may be fit for every vehicle, the number of modules varying from 1 to, say, 20 (these being pre-mounted into one or two racks, for HEV fast swapping). Now if you decide on a different type of battery for HEVs, the problem is that you must satisfy all types of vehicles, from small buses to powerful 40t tractors, and we cannot afford many different types of batteries, or the logistics and equipment type and use would become a costly nightmare.

Therefore, the simplest and most economical option is standard modular batteries, chargers and swapping robots, these last probably of two types, one for LEVs (probably with access from the bottom), and another for HEVs (capable of handling battery racks, pre-mounted in BSSs for fast swap times in HEVs, and possibly with a different form of access to HEVs).

**Conclusion**

Modular batteries, compatible for all vehicles for road transport, light or heavy, is the best choice.

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177 The same misuse of resources would also happen in Plug-in, in future higher autonomy EVs, but to a lesser degree: since the inevitable fast charging accelerates degradation (also a bad use of materials and resources, of course, but intrinsic to the model), the calendar lifetime degradation would not be so relevant in Plug-in.
ANNEX 5: WHY THE COST OF BATTERIES MIGHT BE LOWER WITH BSWAP THAN WITH PLUG-IN, DESPITE THE NEED FOR EXTRA BATTERIES

Within a simple model for battery lifetime increase with BSwap, we demonstrate that, despite the need for the extra batteries being charged in BSSs, the overall cost of batteries may be less, not more, than with Plug-in.

First question: How many extra batteries are needed, to be charged in the battery swap stations, BSSs? It depends on the average residence time of batteries in the BSSs, and on the average electric energy consumption for road transport per day.

Assume that average road transport demand is 60 GWh/day. If batteries were handed into BSSs completely discharged, and handed back fully charged, the battery capacity handled per day in BSSs would be exactly 60 GWh. However, when batteries are swapped, they will have a residual charge, say 15% on average, so the energy supplied per battery is only 85% of its capacity. Therefore, the capacity of batteries passing through BSSs per day is then 60/85% = 71 GWh.

Assume the average residence time of a battery in a BSS is 24h, which is a convenient period for grid energy management: for instance, every battery, while connected, would go through the daily solar peak power generation, and through times of minimum energy demand, with ample opportunity to soak up every bit of excess energy and to buy it at minimum price. In this case, the average energy capacity of the batteries nationally connected in BSSs would be exactly 71 GWh.

This is a very large storage capacity, combined with a nominal power capacity several times the average power in the grid, which would have such a high cost if it were bought and installed on purpose for grid stabilization that it would be well beyond the wildest dreams of a grid operator. The beauty of it is that all this capacity comes free to the grid because it is paid for by transport: EV batteries perform both functions, provide mobility and balance the grid.

But what fraction of the battery capacity on wheels are we talking about? Assume 7 million vehicles with on-board batteries with average capacity of 100 kWh: battery capacity on wheels would be 700 GWh, and that at battery swapping stations (BSSs) would be 10%, if their average residence time is 24h (for a different residence time, proportional to it). Conclusion: BSwap requires extra battery capacity of the order of 10% that on wheels.

Second question: How much would cost these extra batteries? At first thought, simple: it is equivalent of overcharging 10% for every battery in the Plug-in model, making the BSwap model that much more expensive. However, it is not that simple, for one main reason: in our BSwap model, all batteries are charged at a slow rate (one has 24h to do it, in the case discussed above) and in a temperature-controlled environment. BSwap avoids entirely fast charging, and it happens that fast charging, particularly at high or very low ambient temperatures, and high states of charge, is probably the greatest contributor to battery degradation. So, simply because of this reason, battery lifetime in the BSwap model should improve compared to that in Plug-in. There are no hard numbers yet to quantify this, so we opted, conservatively, to assume an average lifetime of 9 years for BSwap, just one year more than for Plug-in, set at 8 years.

178 This corresponds to 22 TWh/year, coherent with 20 TWh/year at the motors, and about 90% efficiency.

179 With our assumption of future cost of batteries at 70 €/kWh capacity, the investment in these batteries would be 5 thousand million euros, to be renewed every lifetime of battery limited duration.

180 Present state-of-the-art batteries may last longer than 8 years in a private passenger vehicle, if its average annual utili-
### TABLE A5.1  Comparison of battery needs in BSwap and Plug-in.

<table>
<thead>
<tr>
<th></th>
<th>Plug-in</th>
<th>BSwap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total battery capacity at ref. year (GWh)</td>
<td>718</td>
<td>790</td>
</tr>
<tr>
<td>Substitute end-of-life batteries (GWh/year)</td>
<td>70</td>
<td>66</td>
</tr>
<tr>
<td>New batt. for market expansion (GWh/year)</td>
<td>38</td>
<td>42</td>
</tr>
<tr>
<td>Total new capacity needed (GWh/year)</td>
<td>108</td>
<td>108</td>
</tr>
<tr>
<td>TOTAL cost of new batteries (M €)</td>
<td>7 559</td>
<td>7 583</td>
</tr>
</tbody>
</table>

When we compute the final cost of new batteries per year within the two models (with the assumption of a 6%/year market growth), the result is interesting: in spite of the extra batteries, the need for new batteries per year, and therefore their cost, within the BSwap model, comes out the same as that in Plug-in\(^\text{181}\), 108 GWh of new battery capacity per year, the higher capacity needed for market growth in BSwap being compensated by the lesser need of replacement of end-of-life batteries.

Note that in a more mature market, the need for new batteries in BSwap would be less than with Plug-in, even with the modest increase of battery lifetime we considered here.

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\(^{181}\) In all our models, a market growth of 6% per year is assumed in this chapter.
ANNEX 6: SYSTEMS DOMINATED BY NUCLEAR ENERGY

What are the consequences of the road transport models in systems with a very high fraction of nuclear power generation?

Presently, nuclear power satisfies a usually small fraction\(^{182}\) of baseline (because reactors work best at constant power output) demand. Therefore, generally, the conclusions of the relative merits of the road transport models are not qualitatively affected.

However, what about France, the present notable exception, with a nuclear fraction of 70\% of generation? And what if the pressure to decarbonize leads to the so-called nuclear renaissance, and several countries over the world decide to bet on massive nuclear generation?

Detailed calculations are always the answer. Here we shall only show, in the very extreme example of a country that decided on 100\% nuclear generation, how the different transport models would fare, and why. This model is totally unrealistic, of course, it is just a tool to help understand the effects of each transport model.

The results are shown in Figure A6.1 for only a few days (with a profile taken from January in Portugal 2050). The dotted horizontal line represents the nuclear generation output, a constant power set precisely so that generated energy equals the average needs of the varying demand during these few days, assumed similar for all the year: another radically unrealistic model, for simplicity, so we can focus on the simpler problem of daily variations, rather than weekly or seasonal.

In the first graph, labelled ICE, the variable curve is the general demand, considered rigid and displaying the typical winter profile of peak demand in the evening, and lowest demand during the first hours of the day. The problem of a constant generation is that it does not follow demand variability, so there will be hours of power deficit, represented in rose, and times of power excess, represented in yellow. Since the system must be balanced, one solution might be to store the excess energy peaks and use this energy to satisfy the deficit peaks, while raising total power generation to compensate the inevitable losses. Another possibility might be to add power peaking generation, such as a gas turbine, and to curtail or export at low price the excess energy. An alternative might be to import energy at peak consumption times and export it at the times of minimum demand. Of course, none of these are cheap, as we discussed above\(^{183}\).

Let us then further explore the results of applying to such a system the three models of decarbonized road transport we studied.

In the graph labelled Plug-in, road transport has been electrified with a Plug-in model. Demand is now the sum of general demand plus transport demand, which was taken as a 25\% increase in demand, and consequently a proportional increase of generation, to satisfy the higher demand, was assumed. Since with Plug-in transport demand is essentially rigid, the cited problems of ICE are now the same, but greater (as discussed above, with Plug-in the capacity to make transport demand flexible is limited): larger peaks of excess and deficit.

BSwap opens the possibility of offering flexibility of transport demand, and the result is shown in

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\(^{182}\) Presently, only 10 countries (a majority of which from the old East European bloc), responsible for 4.7\% of world electric energy generation, have a nuclear contribution >30\%.

\(^{183}\) This is one reason why close to 100\% nuclear generation is not a good idea: France uses its remaining fossil generation, together with renewables, to balance its present, mostly decarbonized, system. Nuclear generation should not exceed, say, 80\% of the generation: you normally would not want nuclear generation to go above the bottom of the seasonal minimum.
the graph labelled BSwap. The lighter blue is general demand, the same as in ICE, and the darker blue area is transport demand, which is now flexible: notice how it is nearly zero in the hours of general demand peaks and is maximum in its night troughs. There is no need for bidirectionality (except as a firm power reserve, and for grid support services), flexibility is sufficient to balance the grid, and the costs of storage, added peak generation, or import/export, are avoided.

**FIGURE A6.1** Satisfaction of demand by a constant power source for each of the mobility models. The dotted line represents the constant power generation. Regions in yellow/rose represent excess/deficit of power, darker blue represents flexible road transport demand. Note the change of scale in the illustration of the H2 case, revealing the higher need of additional generation.

The last graph, labelled H2, shows the result of applying, in this electric system, the H2 model. We assume here that transport demand, represented in darker blue, is also totally flexible, and the result is also a balanced grid, just as with BSwap. The difference is that the low round-trip efficiency of the hydrogen cycle requires a lot more energy for the same transport final demand (measured at the electric traction motors), so generation must be much higher (by some 4 000 MW) than in the case of BSwap, as we can see by comparing the area of the darker blue areas, much larger in H2 than in BSwap. Therefore, it will be more expensive for the electric system to power transport with the H2 model than in the case of BSwap.
We limited this demonstration to an extremely simple example, and focused only on daily demand variations, leaving out longer term variations (such as seasonal), for the sake of simplicity: just the simplest graphical way to represent model differences. This study makes it clear that BSwap may indeed be the better choice for road transport when considering its impact on an electric system, even in this extreme case, and that the resulting relative costs may be the lowest. What BSwap does, in this example, is to compensate the daily variation of demand, which is a much simpler problem than to compensate simultaneously demand and generation variation, as was the case in the Portuguese model.
ANNEX 7: GRID-CONNECTED VS DEDICATED GENERATION

Will additional generation to satisfy road transport demand be grid-connected, stand-alone dedicated, or a hybrid solution? How can regulation encourage virtuous practices, those that optimize global sector outcomes, while fairly distributing the benefits among the various players?

The additional generation needed to power mobility is consumed at the points of electric energy demand for transport: the Plug-in chargers, the H2 electrolyser plants, the BSSs.

*The case of Plug-in*

Let us consider first the case of Plug-in. In the case of Plug-in chargers, the rule will be injection of the additional generation in the grid, and use dispersed, grid-connected, chargers. Only exceptionally will some additional generation be installed near the chargers, generally this makes little sense. Therefore, bringing the generated energy to the consumption points (the chargers) will use intensively the grid.

Also, the relatively high imbalance in Plug-in (despite some demand flexibility and V2G considered in the model) is not taken care of close to the chargers, it will be the result of grid-connected balancing assets (such as pumped hydro storage) far from the consumption points. Therefore, the correction of imbalance will also use intensely the grid.

From our perspective of estimating sector cost differences resulting from the 3 models of e-mobility, we simplified the problem by adding, to the marginal cost of generation, the cost of grid use for stability and for bringing energy to the chargers, namely due to (i) energy losses and (ii) increased grid costs (such as those resulting from additional grid capacity). We greatly simplified this calculation by assuming that these costs may be expressed by an average, guessed, coefficient, that increases the cost of additional generation to reach and satisfy consumption by Plug-in chargers.

*The case of H2 and BSwap*

However, in the case of BSSs and H2 electrolyser plants, would it not be cheaper to have additional dedicated generation close to the consumption points, in a small, private grid? This is highly debatable, since the microscopic interest of a promoter might be contrary to global sector efficiency. And some regulations define tariffs for grid access in such a way that may discourage grid connection, while the global system might benefit from such connections.

Let us illustrate this point with a green hydrogen power plant. The cost of the product, hydrogen produced by electrolysis, is determined by the (i) cost of energy, plus (ii) the cost of the plant (including capital, O&M, ...). Now the same amount of hydrogen may be produced by a plant A, with a high number of electrolyser stacks, but operating 4000 hours/year; or by another plant, B, with a lower number of electrolyser stacks, but operating 4000 hours/year. In case A, the cost of hydrogen will be high, dominated by the cost of the plant, whereas in case B the cost of hydrogen would be lower, energy being the dominant component.

*Grid connected plant*

Consider the case when a hydrogen production plant is grid-connected and procures its energy
exclusively from the grid. If it worked only 1500 hours/year (an average of 4.1 h/day), it would manage to obtain a very cheap average tariff, possibly even below generation cost, using mostly hours of excess generation. For capacity factors over 2500 hours/year (equivalent to 6.85 h/day) the average tariff would of course be higher, but still well below that of regular consumers. The electric system would be happy to sell at these low prices because it helps to balance the grid (while the alternative might be to curtail, or to export at a lower price, this energy – which would make electric energy in general more expensive).

The minimum hydrogen cost will be reached as a compromise between the cost of energy and the investment and operational costs of the plant.

**Dedicated generation**

If the plant procures its energy from a dedicated solar installation, and tries to use most of its energy, it will work with a capacity-factor equivalent to about 2000 hours/year, and plant costs will weigh on hydrogen cost. A combined solar + wind installation is a better solution where possible, even if e.g. the average cost of wind energy is higher than that for solar, because it increases the capacity factor to a higher value. An optimization algorithm will decide on how much wind, and how much curtailment, will minimize hydrogen cost.

Of course, if some excess energy is curtailed, the rest of the energy, effectively used to produce hydrogen, will be more expensive. To illustrate this, assume that the average cost of generation by the dedicated installation is 45 €/MWh. Now, due to the limited power capacity of electrolysers, suppose that 18 % of the generation potential of the installation is curtailed. The remaining 82 % of energy effectively used for hydrogen production has a cost of 45/0.82 = 55 €/MWh, a 22% increase.

**Hydrogen production versus battery charging in BSSs**

In conclusion, the lowest cost for hydrogen (or, more generally, the best outcomes) always requires an optimization process to balance the two coupled contributions, energy and plant cost (including the solar and/or wind generation plants), so that a minimum is reached.

The same applies to battery charging at BSSs, which also compete for lowest cost energy. The main difference between a BSS and a hydrogen production plant is that the optimum point is shifted towards higher power, lower capacity factors, and less curtailment, and therefore to a lower overall cost of the energy it supplies for mobility. The reason is that the investment and operational costs of the battery charging units are lower than those for a hydrogen production plant.

**A hybrid solution**

Assume the same solar + wind generation capacity mentioned above could be installed at the same place, close to the hydrogen plant or BSS (electric generation close to a consumption point is of course interesting, because intensive use of the grid, including perhaps major grid power-line capacity increase, is avoided), but grid-connected. Generated energy will be more efficiently used than if it were dedicated to the hydrogen plant or BSS only, insulated from the grid: the optimization of larger systems always produces a better global result than that obtained by many smaller, insulated, parts.

The electric sector would in general benefit from shared generation and consumption into a single market, rather than a market split into tiny islands; but regulated grid access tariffs are frequently
designed with regular consumers in mind and may represent a barrier for an integrated market in such cases. As an illustration to this point, governments wishing to promote green hydrogen production plants simply exempt private promoters from grid connection tariffs, an obvious confession of unadapted regulation, and an unfair advantage offered to the owner of the hydrogen plant, a hidden subsidy at the expense of others.

This suggests that regulation be modified to stimulate industrial players into processes that may produce virtuous outcomes. The connection of the solar + wind capacity just before or just after the counter does not alter essentially how the global system optimally works, and should result in similar virtuous outcomes, unhindered by regulation. And regulation should also result in a fair distribution of benefits to all players, namely the private owner of the BSS or hydrogen plant, and the global system.

The need for such regulatory modifications is even more visible in the option, suggested in the main text for BSSs, that the management of power supply to battery swap stations, including their bidirectional capabilities, be totally handed to the grid operator.

Coming back to the original question, the answer is clear: when local conditions for low-cost renewable generation exist, and a grid connection is available, a hybrid model, with local generation coupled with the grid, will generally be the better model. Regulation should adapt to encourage it, and fairly distribute returns to all players.
ANNEX 8: DEMAND AND GENERATION
WHEN MOBILITY DEMAND IS FLEXIBLE

A more detailed illustration of how demand and generation adapt to produce low imbalance in the battery swap model.

For the curious reader wanting to better understand the effect of demand flexibility, the same data of Figure 3.11B is displayed in Figure A8.1 in a rearranged form, such that some of the most relevant features of demand flexibility are explicitly shown.

**FIGURE A8.1** An alternative display of the data in Figure 3.11B, to illustrate the effect of flexibility: the original rigid Demand (black dashed line, the same as shown in Figs. 3.1 to 3.11C) is deformed into the new Flexible Demand (continuous black line), which adapts to Total Generation (brown) so well that the residual difference, the Imbalance (blue, the same as in Figure 3.11B) is small. The flexible demand of BSwap batteries (red line) is explicitly seen as capable of (a) completely absorbing the solar peaks, of (b) switching-off battery charging when imbalance is positive (power deficit), and of (c) using other hours of low demand and sufficient generation to complete battery charging.

- The brown line in Figure A8.1 represents the total generation after using its flexible components, hydropower (which includes the use of additional water availability brought about by pumping) and WtE/biomass, to adapt as much as possible to demand (model "Pumps"). As we saw before, in Figure 3.5 and 3.11A, this adaptation is quite insufficient: the remaining difference between generation and consumption, which is displayed as the imbalance function labelled "Pumps", is still large. The same function is not displayed explicitly in Figure A8.1, but can be perceived as the difference between the dotted line (which represents total demand, including mobility demand as rigid) and the brown curve. This imbalance function within model "Pumps" is far from tamed because generation is...
dominated by the rigid components of solar and wind.

• The continuous black line demonstrates the effect of introducing demand flexibility. It results from the deformation of the original rigid demand curve (dashed line) after using its flexible components (water pumping and battery charging) to adapt to the available generation: it is the flexible demand curve.

• This adaptation is successful: the remaining difference between the flexible demand (continuous black) and generation (brown) curves, the imbalance function (the explicitly shown blue line, the same in Figures A8.1 and 3.11B), becomes small, with values perfectly manageable by the electric system at all times.

• The adaptation of the most interesting component of demand, that of battery charging within the BSwap Flex model, is explicitly shown (red line). It shows how battery charging in the BSSs (i) leads to the total absorption of the solar peaks, (ii) lowers total demand at times of power deficit by switching-off charging, and (iii) completes battery charging by modulating its demand according to availability (in times of lower general demand and sufficient generation).

• The other flexible component of demand, hydro pumping, is also interesting to consider, but was equal to zero during all this week of high consumption and low generation, and therefore not visible in Figure A8.1.

This last paragraph may be questioned by the reader: was hydro pumping not responsible for the large improvement, during this very week, displayed by the darker blue curves of Figure 3.11A (and 3.5)? Wasn’t its effect so evident in mopping up most of the negative peaks of the imbalance function? How come there is no pumping to be seen here, in Figure A8.1?

The reason is the following:

• We are not simply taking the results of the “Pumps” model and adding battery charging on top. On the contrary, each time the system is modified, its behaviour is recalculated from scratch.

• Now when we introduce flexible battery charging demand to a system that already has a flexible component, that of hydro pumping, we need to define priorities: which demand should be satisfied first? Battery charging, or hydro pumping?

• Batteries must be handed out to electric vehicles to satisfy mobility, so battery charging must take priority. Once this demand is satisfied, then remaining “excess” generation becomes available for hydro pumping.

• In this particular week, the negative peaks are completely mopped up by the batteries, so there remains no “excess” generation to be used by pumps.

Therefore, in Figure 3.11A, when hydro pumping is the only flexible demand (battery charging being considered rigid), the pumps immediately start absorbing the negative imbalance peaks up to their power capacity of 3.4 GW, so that the only negative peak that remains in part was that of Sunday, too strong to be totally absorbed.

However, in the system displayed in Figure A8.1 (the same of the lower curve of Figure 3.11B), battery charging within a BSwap model is present, and its absorbing power capacity far exceeds that of even the Sunday peak; the result is that no generation “excess” is left for the pumps to be activated.

Pumping does occur frequently in weeks of more abundant generation, after battery demand is satisfied.
In fact, total annual consumption by hydro pumping is observed to remain of the same order when BSwap flexible battery charging demand is introduced: a modest decrease of only about 18% against the case of rigid battery charging is verified.

In Chapter III, when we asked the question “What is the role of each balancing technology?”, we focussed two points in time to exemplify how the interplay of flexible demand and generation (both in hydropower and in BSSs), intrinsic to the BSwap model, produce the excellent results for system balance presented above. Let us review here how those results can now be understood under the representation of Figure A8.1.

**Peak demand point (positive imbalance)**

The first point in time chosen for that analysis was the time with the highest demand in the basic model with rigid e-mobility consumption, the time corresponding to the top of the third evening peak of the dashed line of Figure A8.1.

The very high demand of 16.1 GW was abated by a sequence of contributions. The first one was due to flexibilization of e-mobility demand: the fraction of rigid e-mobility demand under the total 16.1 GW peak demand, worth 4.0 GW, was brought to zero by flexibility, and so was subtracted from the total, as shown in Figure 3.11E. The same effect is seen here, in Figure A8.1:

- e-mobility demand, which has been made flexible, and represented by the red line, has become zero at this time.
- The difference between the the dashed curve (which includes e-mobility rigid demand) and the continuous black curve (Flexible Demand), at the peak point of the dashed curve, is precisely those 4.0 GW.

At this chosen time, the black curve of Figure A8.1 is then brought down to the blue line (the imbalance function after flexibility is introduced), a precipitous fall of 9.4 GW, which is the sum of all the generation contributions (wind at 0.4 GW, waste-to-energy/biomass at 1.5 GW, and, most importantly, hydropower at 7.5 GW) shown in Figure 3.11E.

The final further attenuation of the imbalance function by the action of a battery-to-grid injection, worth 2.0 GW and seen in Figure 3.11E, is not shown here, in Figure A8.1, because the curve corresponding to imbalance within model BSwap+ is not displayed, only that resulting from BSwap flexible e-mobility demand was displayed (the blue line), which does not include battery-to-grid effects.

**Solar peak point (negative imbalance)**

The second point, analysed in Figure 3.11F, is the time of the solar peak of Sunday of the same week, shown in Figure A8.1 as the time of the last e-mobility demand peak of the graph. At this point in time, a (rigid) demand of 11.4 GW is observed, 2.8 GW of which are due to rigid e-mobility demand.

Once we subtract this 2.8 GW contribution and add the present (flexible) e-mobility demand of 11.9 GW (value of the top of the orange line in Figure A8.1), the original demand (black dashed line) grows by 11.9 - 2.8 = 9.1 GW to the black line, the new total demand, at 20.5 GW. This is very nearly matched to the sum of all generation contributions (wind 3.0 GW, solar 15.1 GW, WtE/Biomass 0.2 GW, and hydro at 2.1 GW), which total 20.4 GW, represented in Figure A8.1 by the brown line. This nearly perfect match is also revealed in Figure 3.11F by the very low residual imbalance of 0.1 GW (which, added to the B2G contribution of 0.2 GW, ends with an imbalance of 0.3 GW, seen in Figure 3.11F but not in Figure A8.1.)