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ADVANCED INDUSTRIAL CASE STUDIES

Electric Cars: Sustainability and Eco Design

Claes Fredriksson, Fernando Coelho, Luca Petruccelli and Tatiana Vakhitova

Granta Design, 300 Rustat House, 62 Clifton Rd, Cambridge, CB1 7EG, UK

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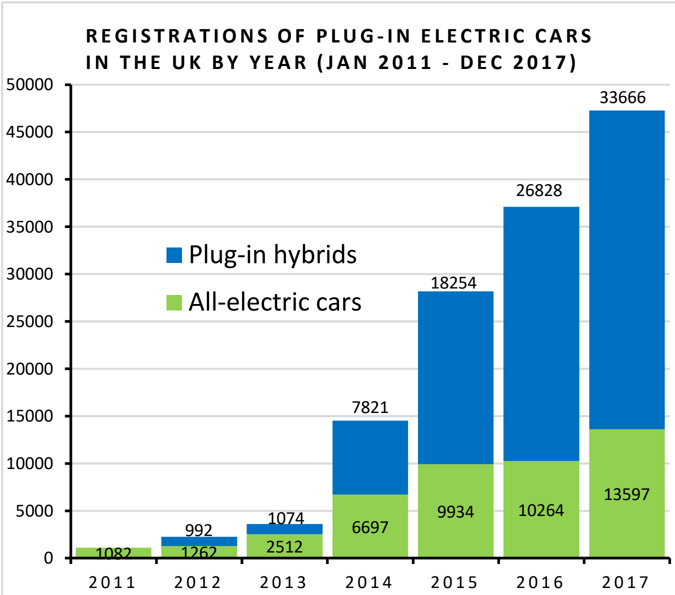
Summary

CES EduPack not only provides a rational and systematic approach to materials selection, it also has useful data and tools to assess the sustainability of products and technologies in development. This is essential for the purposes of future teaching or training within engineering and design. The available databases facilitate informed materials-related decisions in many specialized areas. In this advanced industrial case study, we have used the Eco Audit tool to compare pure electric and hybrid options with gasoline cars. We also focus on critical elements in materials used in crucial parts of an electric car, and benchmark existing options. This highlights the link between the sustainability and performance of these vehicles.

1. Scope

Electric vehicles are currently experiencing a surge in interest because of their potential to reduce pollution, greenhouse gas emissions, and running costs, while also retaining high performance. Therefore, they make for an interesting and current subject to engage students in materials-related courses. Although the internal combustion engine (ICE) is likely to remain dominant in the short and medium term, electric vehicles are expected to have significant and rapid growth over the coming decades, during the transition towards sustainable mobility. The International Energy Agency (IEA) estimates that the global stock of electric cars – including both plug-in hybrids or fully electric – may exceed 9 million per year in 2020, and 20 million by 2025 [1]. By looking at the options available to car designers, we seek to enhance understanding of material decisions and their consequences.

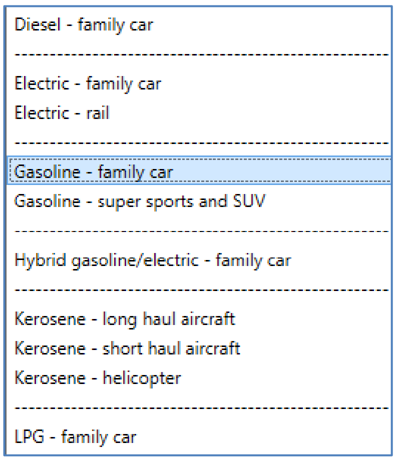


Society of Motor Manufacturers and Traders (SMMT) (2018-01-05). "December – EV registrations".

One issue that has grown with increasing sales of electric vehicles is reliable and sustainable access to certain critical raw materials (CRMs). The high demand for CRMs and limited natural abundance give rise to serious concerns for supply. Diversification, substitution, reduction or improved recycling of these materials have been proposed as possible solutions to this problem. The automotive industry is one of the world's largest, with increasing numbers of CRMs being used generally in vehicles production [2]. This includes elements, such as niobium and the platinum group metals (palladium, platinum and rhodium) [3]. Electrification of passenger cars also demands the increased use of rare earth elements, such as neodymium and dysprosium for the motors [3], as well as lithium, cobalt and graphite for on-board energy storage.

2. What can EduPack do?

The eco-properties and sustainability aspects of products are not obvious, even when you know or can see the materials involved. The whole life-cycle has to be considered (or several life-cycles, for circular economy). The challenge is usually to select materials to maximize several relevant aspects; for example, both mechanical and environmental properties, taking into account feedstock and end-of-life options for the product. For eco design, CES EduPack offers several opportunities to investigate and discuss sustainability. In the case of electric cars, a good starting point is an Eco Audit to investigate characteristics of the spectrum of vehicles mentioned above; Gasoline for ICE (reference), hybrid or plug-in hybrid cars and fully electric cars. The Eco Audit offers an overview of the relative importance of the material phase, the manufacturing and use phases, as well as the possibility to study the effect of material recycling [4].



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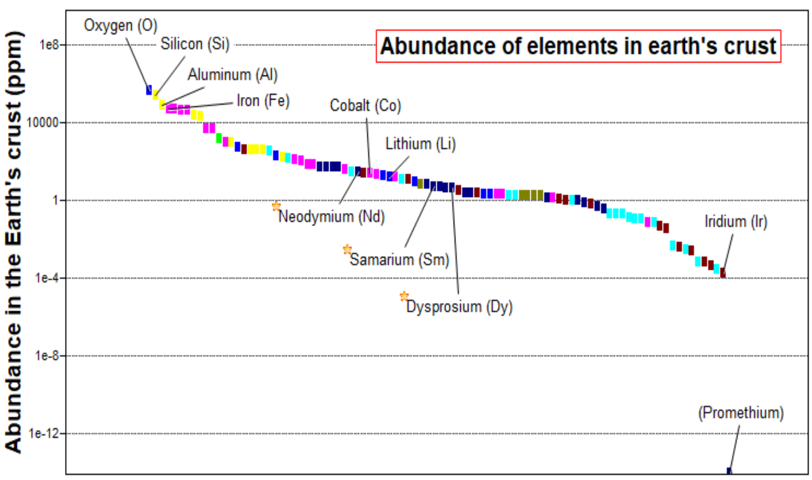
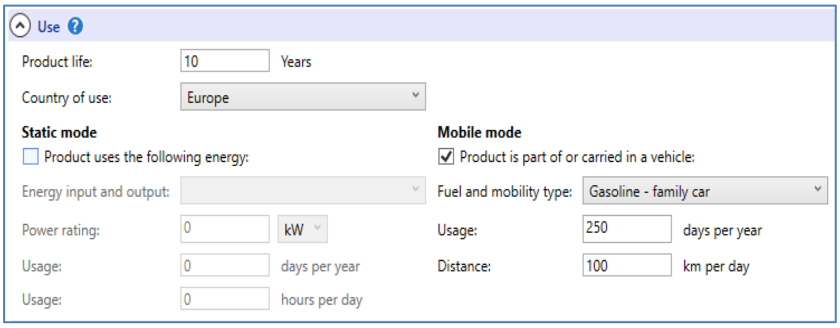


When it comes to investigating electric motors and batteries, there are many useful features in CES EduPack which can be employed. Performance aspects of both electric motors and batteries can be visualized, using charts and relevant property data. These can clarify why Li-ion batteries and Nd-based magnets are preferred technologies. Information on critical materials, particularly lithium, cobalt, rare earths, and their main mining areas, are available within the Elements database/data-table.

3. Eco Audits of powertrain options

The *use phase* of Eco Audit consists of two modes and options for *country of use*. The *mobile mode* is well suited for basic vehicle analysis, and makes use of the transport data in the software for different types of vehicles and fuels. It gives average energy use and CO_2 emissions per km and kg for typical vehicles.



A useful Bill-of-Materials (BOM) can be found among the sample Eco Audit project files, which are embedded in the software, normally on your local disc C:\Program Files (x86)\CES EduPack 2018\Samples\eco_audit\en. It contains simplified data for a typical family car at Level 3 (or 2), that can be used or tailored for easy comparisons and visualizing trends. Here, we have modified it in order to represent four different cases (#1-4). Moreover, the Eco Audit can be extended to mimic plug-in hybrid cars, which are not included in the vehicle options. The use phase for these depend on the extent to which electricity can be used in the daily ride.

To keep effort down, we have adapted the sample Eco Audit file by just reducing the Al component in the BOM by 200 kg, down to 238 kg, which is more in line with a typical mid-size car. We have summarized some data from VW golf in the Table to the right. VW Golf is a good example for comparison, since it exists in gasoline (ICE), plug-in hybrid (GTE) and fully electric (e-Golf) versions.

Model	**Golf ICE**	**Golf GTE**	**e-Golf**
Battery capacity	-	8.7 kWh	24.2 kWh
Battery weight	-	120 kg	318 kg
Car weight	1318 kg	1515 kg	1540 kg

You can start the comparison by adapting the BOM for the reference (gasoline) case (#1). We have used the *Sustainability Level 3* database. Click the Eco Audit button in the tool bar and then the *Open* button within the Eco Audit project. Find the appropriate Eco Audit project file in the link on your local disc, as described above. Use Level 3 – Family car (Level 2 will work if you are within the Level 2 database). The mass of Aluminium can be modified directly in the BOM. By replacing the default 438 kg with 238 kg, we reduce the total weight for the car to around 1500 kg. In some modern cars, like the Golf 1.2 TSI, an Aluminum engine weighs less than 100 kg. We have also added to the *product definition* in the Eco Audit, a local transport of 1000 km from the factory, by 26 tonne (3 axle) truck, and consider, as shown above, 10 years *product life* with use in Europe.

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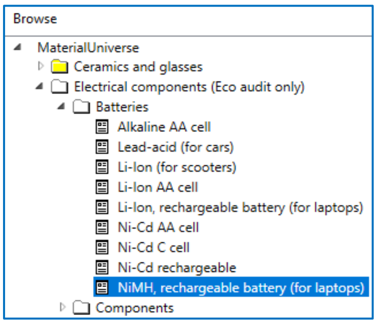
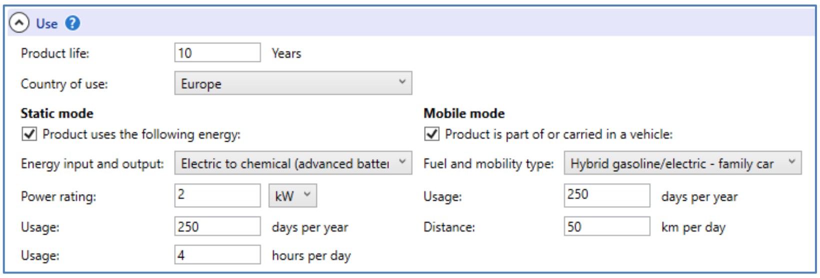
Qty.	Component name	Material	Recycled content	Mass (kg)	Primary process	Secondary process	% removed	End of life	% recovered
1	Steel content	Low alloy steel, AISI 3140...	Typical %	850	Roll forming		0	Recycle	100
1	Aluminium content	Aluminum, 355.0, per...	Typical %	238	Casting		0	Recycle	100
1	Thermoplastic content (PU	TPU(r) (molding)	Virgin (0%)	148	Polymer extrusion		0	Landfill	100
1	Thermoset content	Polyester (cast, rigid)	Virgin (0%)	93	Polymer molding		0	Landfill	100
1	Elastomer content	Butyl / Halobutyl rubb...	Virgin (0%)	40	Polymer molding		0	Landfill	100
1	Glass content	Borosilicate - 2405	Typical %	40	Glass molding		0	Recycle	100
1	Other metal content	Copper, C14200, hard (to...	Typical %	61	Extrusion, foil rolling		0	Recycle	100
1	Textile content	PE-LD (molding and e...	Virgin (0%)	47	Polymer extrusion		0	Landfill	100



A hybrid electric (HEV) car scenario (#2) can be created by using the *Compare with…* option and use *copy of current* (lightweighted) family car. In the *use* phase specification, keep the previous/default values and choose Hybrid gasoline/electric – family car in the *Mobile mode.* This gives a rough estimate of energy use and emissions per km and kg for hybrid cars. In order to account for the battery mass in electric cars adding significant weignt, we have chosen to include 42 kg of the *NiMH rechargable battery (for laptops)*. For hybrid batteries, we can use special records available under the Electrical components folder in the MaterialUniverse.

Now, a traditional hybrid car, such as the early Toyota Prius, are still gasoline cars, although with a more efficient powertrain. Therefore, the country of use and its local energy mix, for example, will not affect the CO_2 emissions. In order to benefit from the advantages of electrically powered vehicles, a *plug-in* hybrid (p-HEV) must be considered (#3). This is an increasingly popular option, as can be seen in the diagram on the first page. The need for batteries will be greater than for regular hybrids but less than fully electric vehicles. For the plug-in hybrid, we make another *copy of current product* and modify the battery to 120 kg of *Li-ion rechargable battery (for laptops)* mimicing the Golf GTE. Tesla actually use similar mass-produced batteries for their cars.



The inclusion of the plug-in hybrid is tricky, since it depends on your travelled distance on respective fuel in *the product use phase* (not transport). We have assumed that the daily distance of 100 km is kept, but that 50 km is from using gasoline, and 50 km from the battery (50 km is the official battery range of the golf GTE). The performance on gasoline will be comparable with the hybrid family car in *the mobile mode*, but the distance on electricity will use stored energy. However, this energy is acquired by charging the battery and can thus be included in *the static mode*. Again, using data from the Golf GTE, charging from the grid will involve energy conversion, with some losses, from *electric to chemical (advanced battery)*. The battery capacity is around 8 kWh so it can be charged at home using around 2 kW of power for 4 h. It needs to be charged every day the car is used, thus, 250 days per year. Ten years might be an optimistic life-expectancy, but the battery warranty covers eight years which indicates a substantial product life.

Finally, the fully electric (EV) car (#4) can be covered by one of the mobile use modes, and the range is normally at least 100 km. In analogy with the plug-in hybrid case, though, we will assign the use phase of 100 km under *the static mode*, approximated by 2 kW for 8 h, 250 days per year (double that of plug-in hybrids). This includes additional energy losses associated with charging an advanced battery, rather than looking at the average energy consumption on the road. It does, however, depend on getting the charging time right. The differences between the static and mobile modes is a good topic for discussion in the classroom. The other main adjustment necessary for the fully electric car is to reduce the BOM by 100 kg of Al to account for not needing the ICE, and a battery mass of 318 kg to account for the Li-ion batteries used (data from e-Golf).

This completes the Eco Audit product specifications and some main results are shown in the summary charts below. They show the main trend of increasing material energy and decreasing use energy in the scenarios.

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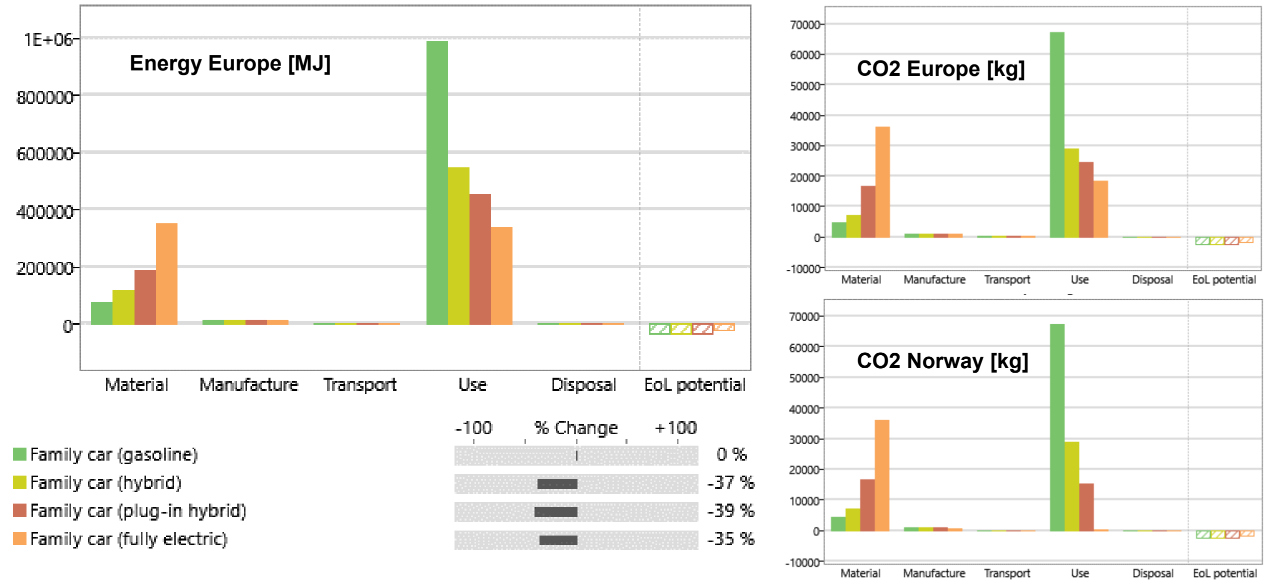

As can be seen in the main chart, the contributions for manufacturing and transport are negligible. In our very simplified scenarios, the energy benefit is comparable in all the three electrified cases: a 35-38% decrease. The associated CO_2-emissions are shown to the right, with a European energy mix used at the top. The case of Norway as the *Country of use* highlights the impact (#3-4) of fully renewable electric energy (Hydro power).

4. Materials in vehicle design

There has been an increase in the number of part components in cars over the past few decades, which has led to an increase in average vehicle fleet weight and power. While some weight reduction has been achieved by deployment of technologies such as unibody construction, more efficient and/or smaller engines, and lightweight materials, this reduction has been offset by the inclusion of new and/or better functionalities and features. Materials use in the automotive industry is broadly discussed in the automotive material flow analysis literature. Until recently, those discussions have focused on traditional materials that represent the majority of total vehicle mass, such as steel, iron, aluminum, polymers, glass, copper, lead, zinc, and "other metals". While this accounts for most of the vehicle weight, it does not represent smaller amounts of critical materials, typical of electric and other modern vehicles [2].

Lithium-ion is the reference technology for electric car batteries, and only to a lesser extent are other battery system, such as NiMH used. In addition to lithium, cobalt and graphite are also employed in these batteries. There are also several rare earth elements in permanent magnets for electric motors. These are some of the elements most affected by increasing EV demand. Among the rare earth elements, neodymium, praseodymium, dysprosium and terbium are used in high-performance magnets and electronic sensors for the standard automotive industry, including starter motors, brake systems, seat adjusters and car stereo speakers.

Battery performance

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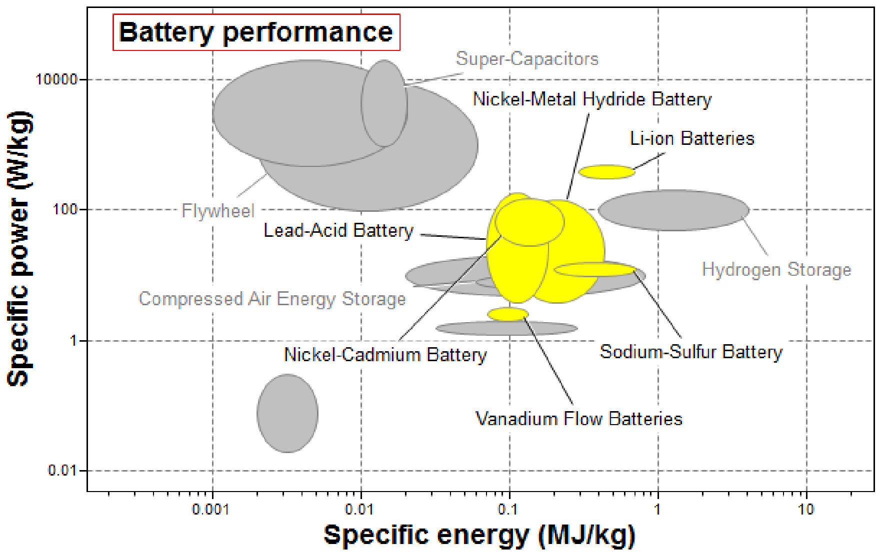
One crucial aspect of electric car development is the on-board energy storage. This determines the range of these vehicles, but also affects the demands on the infrastructure of charging stations. These are concerns for both customers and electric car manufacturers. The *Power System* data-table, available at Level 3 in the sustainability database, offers information and data on a number of energy storage types, and even some mechanical ones, such as flywheels or compressed air. The most popular current battery type for electric cars is based on Lithium-ion technology. The reason for this can be visualized by plotting an overview of performance, and comparing different battery types.

The chart to the right shows why Li-ion batteries are superior for electrochemical energy storage on vehicles. They provide high energy storage per kg of battery, and excel at the power they can deliver per kg. We have highlighted the *Electro-chemical storage systems* but also include other systems. Another relevant performance metric, *energy density* (not shown), measuring the stored energy per volume of space, follows the same trend.

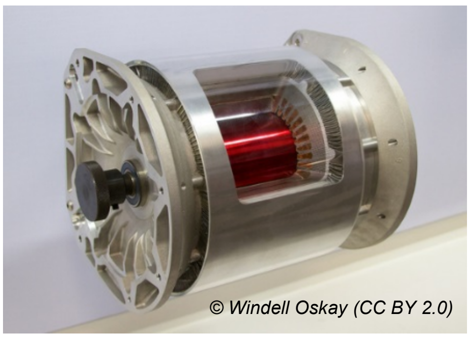


Congo, Democratic Republic of the (COD)	
Datasheet view: Nations of the World	Show/Hide
Human Rights & Good Governance	
Death penalty	Applied
Rule of law index (0 - 100)	3
Control of corruption index (0 - 100)	9
Political stability/no violence (0 - 100)	4
Press freedom index (0, constrained - 100, free)	47.3
The good country index	153
Ongoing conflict?	✓

Lithium has many advantages as charge carrier, since it is a light element. Unfortunately, this element is also a limited resource, which creates problems for mass scale production and challenges to a recycling system. The current lithium electrodes also rely on cobalt, which is a well-known conflict mineral, since it is produced mainly in the Democratic Republic of the Congo. Since there are ongoing conflicts and very poor governance, Cobalt is critical both for EU and US.

Electric motor performance

There are several competing technologies for motors in current electric cars on the market. Tesla has attracted a lot of attention working with an induction-type motor, which is magnet-free, in their previous models. Toyota Prius hybrid cars have been using a permanent magnet based type motor which enables higher efficiency, reducing electrical heat losses and, in the end, the need for battery capacity. The best permanent magnets, however, contain rare-earth elements, which raises questions about criticality and supply-chain issues, as well as associated negative environmental impact during their extraction and refinement.



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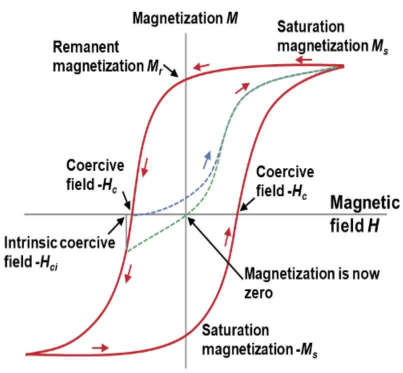
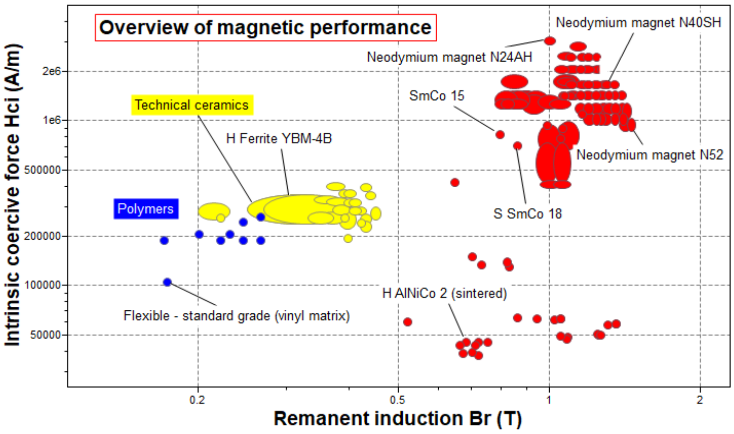
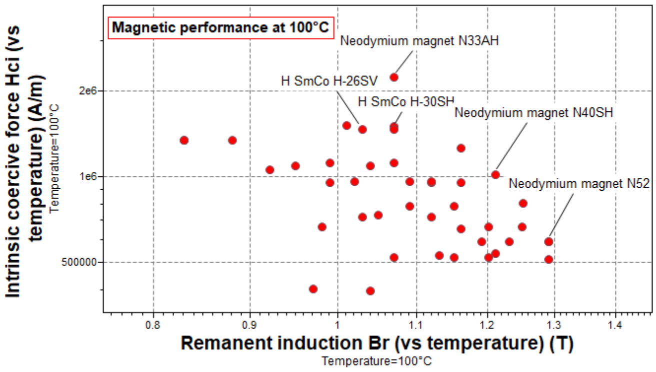


Magnetic design is based on the B-H curve, or hysteresis loop, which characterizes the material. This curve describes the cycling of a magnet in a closed circuit as it is brought to saturation, demagnetized, saturated in the opposite direction, and then demagnetized again under the influence of an external magnetic field. Hard magnet performance is determined by its maximum energy product $(BH)_{max}$, which is a measure of the magnetic energy which can be stored per volume in the material. It is the largest area rectangle that can be inscribed inside the upper left quadrant of this curve. CES EduPack provides magnetic data relevant to this performance in the *Magnetic materials* subset of the *MaterialUniverse, Level 3*. The *Maximum energy product* $(BH)_{max}$, *Coercive* (H_c) and *Intrinsic coercive fields* (H_{ci}) as well as *Remanent induction* (B_r) data exist [5].

The performance for hard magnets (wide hysteresis loop) can be found simply by using a bar chart of $(BH)_{max}$. However, this approximately corresponds to finding a combination of high intrinsic coercive force (reflecting resistance to demagnetization), and high remanent induction (how powerful it is). A chart showing these two properties individually can be seen to the right. Neodymium based and samarium-cobalt magnets display the best performance (upper right hand corner of the chart).





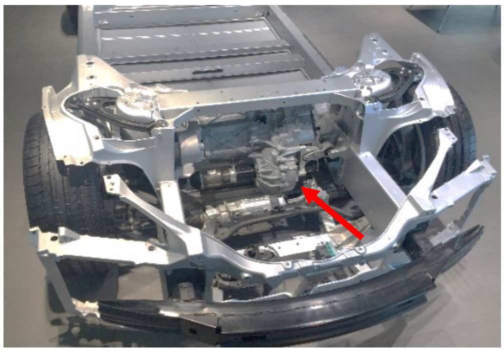
Dysprosium, for example, can be added in order to resist demagnetization at high temperatures. To investigate more realistic temperatures for cars, the temperature-dependent magnetic properties in CES EduPack can be used. It is easy to modify the parameter in the software to, say 100°C. The result shows that the best remaining magnets are clearly the Nd and SmCo based ones. Information about the nomenclature and denominations of these two particular types of magnet can be found in the folder-level records in the Browse tree.

5. Reality check

There are two recent and interesting developments in the area of electric cars and critical materials. Firstly, Tesla has developed their Li-ion batteries to reduce the cobalt content by using Ni-Co-Al cathode chemistry with the Lithium. It is now claimed to be 2.8%, considerably less than previous Co content. Since the Co price has been increasing, and the sourcing is problematic from a sustainability point of view, this is a positive development. Some types of cathode materials are shown below, the middle one being a common choice [6].

Cathode *Metals*	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (Gaines) *mass%*	$LiMn_2O_4$ (Gaines) *mass%*	$LiNiMnCoO_2$ (Richa) *mass%*	$LiCoO_2$ (Wang) *mass%*	$LiFePO_4$ (Wang) *mass%*
Aluminum	21.9	21.7	22.72	5.2	6.5
Cobalt	2.3	0.0	8.45	17.3	0
Copper	13.3	13.5	16.6	7.3	8.2
Iron/Steel	0.1	0.1	8.79	16.5	43.2
Lithium	1.9	1.4	1.28	2.0	1.2
Manganese	0.0	10.7	5.86	0	0
Nickel	12.1	0.0	14.84	1.2	0

Secondly, Tesla has now also introduced NeFeB magnets in their motor technology. These require rare earth elements but reduce the weight and electric losses in the system. Motors based on magnetic material are heavier and more expensive than induction-type motors, but have less heat loss which make them more efficient. By using a sintered NdFeB magnet, it has been possible to increase the performance and further reduce the volume needed for an electric motor. The picture to the right shows how the electric motor (one for the front wheel pair and one for the rear) is integrated in the platform of the car.



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6. What does CES EduPack bring to the understanding?

CES EduPack is an excellent resource for teaching eco design and investigating issues related to sustainability. Working with interactive visual tools, the educator can easily show how to make good materials decisions, and students can explore ways to select and assess materials in realistic projects. Our A*dvanced Industrial Case Studies* are intended to inspire and guide product development, provide necessary knowledge and facilitate the understanding of the subject.

In this case study, CES EduPack suggests the following conclusions for electric cars:

- When developing products and learning about product design, it is important to look at the entire life-cycle as early as possible. The Eco Audit tool facilitates this, and has been used in this case study to understand different powertrain options for cars.
- The Sustainable Development database has a large number of specialized materials and other data, organized into useful subsets. We have successfully explored *magnetic materials* for electric motors and *energy storage* data-tables for batteries. In addition, the extensive *criticality data* has proven useful.
- The *visualization tools* quickly let us have an overview of properties to compare different options for systems showing, for example, that the Li-ion battery is a very competitive alternative and that Neodymium permanent magnets have the best performance.

We do, however, emphasize that the results are estimates from an Eco Audit, which is a streamlined life-cycle inventory. It contains approximations and is based on eco data that has considerable uncertainties. The results are intended to be used as a basis for discussion, and should not be taken as actual values for any of the cars mentioned in the text.

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