Sustainability Case Study

Electric Vehicles

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Summary

If a proposed sustainable development is going to make any significant difference it has to be on a large scale and probably disruptive. This case study illustrates the challenges that must be anticipated in implementing large-scale disruptive technologies.

This resource is divided into two sections: a handout to be used with students in the classroom and an example assessment. There is also an associated lecture presentation.

Referenced websites were accessed at the time of the first publication date.

Table of Contents

Electric cars-- Handout

The proposal

The global production of cars in 2014 was 68 million per year, growing at 2.5 % per year. Cars account for 75% of production of motor vehicles and are responsible for about 20% of all the carbon released into the atmosphere[1]. National governments implement policies to reduce this source of emissions through taxation and incentives. One of the incentives is to subsidize electric vehicles (EVs).

From a materials point of view, the major differences between electric and internal combustion (IC) cars are the replacement of the IC engine with electric motors that, at present, use Neodymium-Boron permanent magnets and the replacement of gasoline or diesel fuel by batteries. It is estimated that the global production of electric cars – either hybrids (HV), plug-in hybrids (PHV), or fully electric (EV) – will exceed 16 million per year in 2021 and will account for 20% of all vehicles manufactured[2]. EVs, particularly, are seen as the way to decarbonize road transport. To meet emissions targets, France, Germany and the UK want 10% of all car sales to be fully electric vehicles by 2020. Is this a realistically achievable sustainable development on a global scale?

Background information

- Today's electric cars have 16 kWh batteries and a claimed range of up to 100 km between charges.
- An EV with this range requires about 1.5 kg of Neodymium for the motors[3] and 7.3 kg of lithium, (equating to 0.46 kg Lithium per nominal kWh) for the rechargeable batteries[4].
- The at-wheel energy required to propel a small car is between 0.6 and 1.0 MJ/km (0.17 and 3 kW.hr/km)[5].
- Delivered electric power from a gas-fired power station has a carbon footprint of 500 g/kW.hr, or 140 g/MJ[6]; that from a coal fired power station has larger carbon footprint.

1 http://www.oica.net/category/production-statistics/2014-statistics/
2 http://imsresearch.com/news-events/press-template.php?pr_id=2135
3 www.reuters.com/article/2009/08/31/us-mining-toyota-idUSTRE57U02B20090831
4 Tahil, W. (2010) "How Much Lithium does a LiIon EV battery really need? www.meridian-int-res.com and http://www.google.co.uk/search?sourceid=navclient&ie=UTF-8&rlz=1T4ADBR_enGB321GB323&q=how+much+lithium+is+in+a+battery
5 Telens Peiro, L. Villalba Mendez, G. and Ayres, R.U. (2013) "Lithium: sources, production, uses and recovery outlook" JOM Vol 65, pp. 896 – 996.
6 See, for example, www.defra.gov.uk/publications/files/pb13773-ghg-conversion-factors-2012.pdf Table 3c

This resource follows the five-step method, which is simply explained below and explained in detail elsewhere.

- What is the prime objective? What is its scale and timing? What is the functional unit?
- Who are the stakeholders and what are their concerns?
- What facts will be needed to enable a rational discussion of the proposal?
- What, in your judgment, is the impact of these facts on Natural, Manufactured, and Social Capitals?
- Is the proposal a sustainable development? Could the objective be better met in other ways?

Where can Granta EduPack help with Fact Finding?

The **Materials data-table** has records for permanent magnet and battery materials such as lithium that include data for price, embodied energy, carbon and water footprints and recycle fraction.

The **Regulations data-table (Level 3 Sustainability)** includes records for regulations relating to transport, batteries and recovery and recycling of vehicles.

The **Eco Audit Tool** allows a fast comparison of the carbon footprint of the alternative material choices.

The **Nations of the world data-table (Level 3 Sustainability)** contains records for the environmental, economic and societal statistics of the nations from which elements are sourced.

The **Power Systems – Energy storage data-table (Level 3 Sustainability)** has data for battery types and their characteristics

The **Graph facility of Granta EduPack** allows data to be plotted as property charts, annotated, and saved to Word Documents.

Electric Cars-- Example of Assessment

The number of the sections corresponds to that of the 5 steps of the analysis. Granta EduPack databases help with fact-finding in ways described int he handout for this case study.

Step 1: the objective, size, time scale, and functional unit

- **Objective:** the de-carbonization of road transport
- **Size scale:** 10% of existing car production globally, equating to 8 million cars per year
- **Time scale:** by 2020
- **Functional unit:** 8 million cars

This immediately poses some critical questions:

- Electric vehicles are charged from the National Grid, at present gas or coal-fired in most countries. Do fully electric vehicles really reduce emissions?
- Is there sufficient over-capacity in electric power generation to cover charging of electric vehicles increasing in number by 10% per year?
- What materials are used in electric cars that are not used in today's conventional vehicles? Today's EVs use lithium-ion batteries to drive permanent-magnet electric motors; the motors use neodymiumboron alloys for the magnets. Is the global production of lithium and neodymium sufficient to cope with the production of 8 million cars per year?

These are questions to research in Step 3, Fact-finding.

Step 2: stakeholders and their concerns

The national press reports the views of government, industry and the public about electric cars. Here are seven examples

1. In his 2011 State of the Union address, widely reported, President Obama called for putting 1.2 million electric vehicles on the road by 2015. This equates to 10% of the annual car sales in the US. Today, in 2016, it is clear that this wish was not fulfilled.
2. "Bloomberg Endorses Preparing Parking Spaces for E.V. Charging." (The New York Times, 14 February 2013). The mayor says he wants New York City to be a "national leader" in electric vehicles
3. "That Tesla Data: What It Says and What It Doesn't."(The New York Times, 14 February 2013). The New York Times reporter responsible for covering energy, environment and climate change discovers the hard way that the claimed range of electric cars is sometimes a little overstated.
4. "CO2 emissions 0 g/km." (The London Times, 24.February 2013). Advertisement for Nissan Leaf.
5. "Are electric cars bad for the environment?" The Guardian 4 February 2013) Norwegian academics argue that electric cars can be more polluting than claimed[7].
6. "Leaf stalls" (The London Times 5 March 2013). Nissan admits that customers hesitate to buy its Leaf EV because of price and range anxiety.
7. "Biofuels could cut CO2 'cheaper than electric cars'" – Businessgree.com report the conclusion of a new (2013) report commissioned by oil giant BP, which part-owns the Vivergo ethanol plant[8].

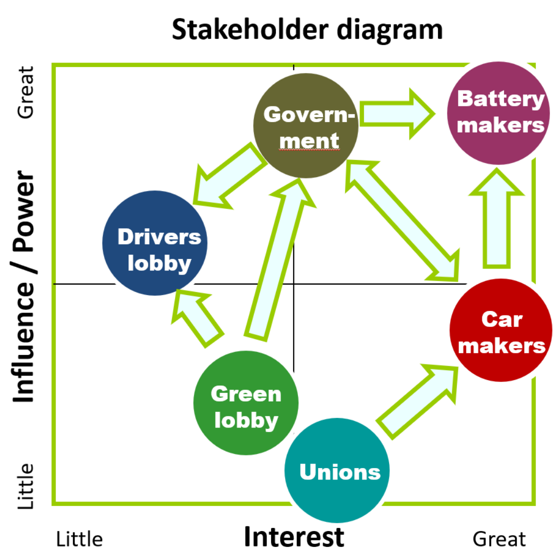

Figure 1: Stakeholder interest and influence

7 http://www.bbc.co.uk/news/magazine-22001356

8 http://www.businessgreen.com/bg/news/2295231/report-biofuels-could-cut-co2-cheaper-than-electric-cars

These reports give an idea of the controversy surrounding electric vehicles. They also give an insight into the stakeholders and their concerns and relationships (Figure 1). Among them are those listed in Table 1.

Table 1: Stakeholders

Stakeholders	Concerns
National governments	To meet carbon-reduction targets and to reduce dependence (where it exists) on imported hydrocarbons
City or state administrations	Provisions of charging points and specialized recycling facilities, particularly for battery materials
Car makers and their suppliers	Consistency of Government policy to support a market for electric cars, secure sources for essential materials and public acceptance of electric cars
Battery makers	Secure supply chains for the raw materials of the batteries, which include Lithium and Rare earth elements
Resource-rich nations	Retaining control of materials supply chain and protection of domestic car and battery makers
Oil companies	Retaining a share in the provision of fuels for future transport systems
Labor unions	Job-creation, stable employment, and improved pay and working conditions in the automobile sector
Automobile associations, drivers	Range, battery life and replacement cost, and depreciation of electric cars
Green campaigners	The damaging impact of gasoline and diesel-powered cars on the environment.

Are these concerns valid or (if they are not) can they be refuted? That is a further job for Step 3, Fact finding.

Step 3: fact finding[9]

What information is needed to support or refute the claims made for electric cars and the concerns expressed about them? What additional facts do we need for a rational discussion of the Prime Objective – 10% of cars fully electric by 2020? These questions are explored in the sections below.

Energy and power. Batteries are heavy. Weight is minimized by selection the battery with the highest energy density. Figure 2 plots the energy density for energy-storage systems[10]. Lithium-ion batteries out-perform all other battery types, although their energy density, 0.6 MJ/kg, is still a factor 75 less than that of gasoline or diesel fuel. The at-wheel energy required to propel a small car is about 0.6 MJ/km. Thus the battery weight per unit range is roughly 1 kg/km. An acceptable range of 500 km (300 miles) would need a battery weighing half a tonne and costing, at today's prices, about $50,000.

There are about 1 billion cars on the world's roads. If 10% of these were EVs, driven 17,000 km (10,000 miles) per year, each consuming 0.6 MJ/km, they would draw *108 x 0.6 x 17,000 = 1012 MJ / year* from the national grid. An average power station produces 4 x 1010 MJ / year, so 23 additional power stations would be required to charge the cars. A country the size of the UK, France or Germany would require at least one additional power station to cope.

9 http://msl.mit.edu/publications/HandDryingLCA-Report.pdf
10 MacKay, D.J.C (2009) "Sustainable energy – without the hot air" UIT Press, Cambridge, UK and Ashby, M.F. (2013) "Materials and the Environment" Butterworth Heinemann, Oxford

Figure 2 is made with the Energy Storage data-table of the Sustainability Database. You can add the data for gasoline and diesel fuel the data-table, right-clicking on the header and selecting "New record". Insert a name ("Gasoline") in the top box, scroll down to "Specific energy" and enter values (43 to 46 MJ/kg). Do the same for a second new record ("Diesel fuel"). Then create a plot of Specific Energy. It will look like Figure 2.

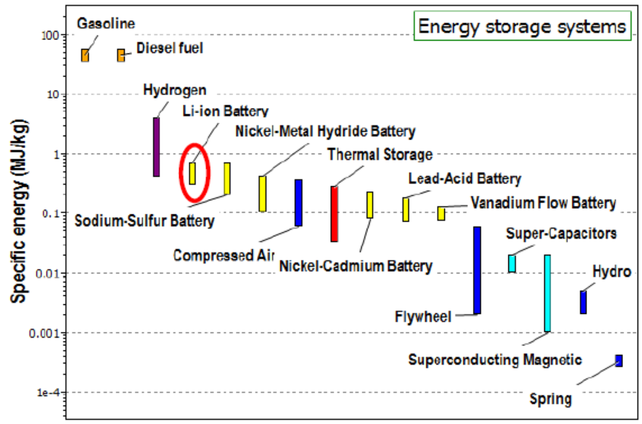

Figure 2: The specific energies of alternative energy storage systems using the Energy Storage data-table

Materials. One element of interest here is Lithium (Li). Table 2 lists that main producers. The annual world production of Lithium at present stands at 34,000 tonnes per year. The supply-chain of Li is relatively diverse – 67% comes from Chile and Australia, the rest from a range of other Nations.

The envisaged production of 16 million electric cars per year, each with 16 kWhr battery pack requiring 7.3kg of Li, would, if battery design is unchanged, require *7.3 x 8,000,000 ≈ 58 x106 kg ≈ 58,000 tonnes of Li / year* or 170% of current world production. If car-range is extended to meet consumer concerns the demand would be higher unless an alternative storage system can be found.

The supply-chain and availability of Neodymium (Nd) can be researched in a similar way. Here is a summary of the position. The present annual global production of Rare earths metals is about 134,000 tonnes per year, of which 15% (20,000 tonnes), on average, is Neodymium. Over 95% of supply is from a single nation. The envisaged production of 16 million electric cars per year, each containing 1.5 kg of Nd would require, using today's technology *1.5 x 8,000,000 ≈ 12x106 kg ≈ 12,000 tonnes Nd / year.*

This is 60% of current global production. There are no substitutes for Nd-based magnets that offer the same performance, so the constrained supply-chain is a concern.

Table 2: Lithium producing nations (2012 data)

Nation	***Tonnes/year***
Chile	12,600
Australia	11,300
China	5,200
Bolivia	5,000
Argentina	3,200
Portugal	820
Zimbabwe	470
Brazil	160
World	**34,00**

Minerals.usgs.gov/minerals/pubs/commodity

Table 2 is copied from the Elements data-table of the Sustainability Database. It lists the countries of origin of materials and the contribution of each to total world production.

The Environment – can the Prime Objective be met? Electric cars will be charged from the National grid. Consider the carbon footprint of the car if the grid is largely fed (as in many Nations it is) by gas-fired power stations. Delivered electric power from such stations has a carbon footprint of 500 g/kW.hr, or 140 g/MJ[11]. The energy in the form of gasoline or oil required to propel an efficient small car is about 2 MJ/km[12]. The conversion

11 See, for example, www.defra.gov.uk/publications/files/pb13773-ghg-conversion-factors-2012.pdf Table 3c
12 An efficient small car does about 16 km/litre of gasoline. One liter of gasoline has an energy content of 35 MJ/liter.

efficiency from gasoline to crankshaft power is at best 1/3, so for equivalent performance the electric motor replacing the IC engine must deliver about 0.6 MJ/km. The combined efficiency of a lithium ion battery / electric motor set is at best 85% when the recharge cycle is included, so electrical energy of 0.6/0.85 ≈ 0.7 MJ /km must be provided from the grid. This carries a carbon penalty of *140 x 0.7 ≈ 100 grams per km.*

The median carbon emission of today's cars is about 200 grams per km, but a number of contemporary models already emit less than 100 grams per km. Thus until the grid is decarbonize, carbon emissions from electric cars are no lower than those from an efficient gasoline or diesel powered vehicle. Power predominantly from nuclear sources (as in France) or from renewable sources (Norway, Iceland) changes the equation.

The records in the Power Systems data-table of the Sustainability Database list the carbon footprint per MJ and kW.hr of both fossil fuel and low carbon electricity generating plant.

Legislation and Regulation. A search for legislation relating to private vehicles retrieves a number of European Directives and US Department of the Environment Acts:
European legislation:
- EU Automotive Fuel Economy Policy on carbon emissions
- Fuel taxes
- EU Battery Directive
- End-of-Life Vehicles Directive (ELV)

US legislation
- CAFE rules
- Fuel taxes

All have a bearing on the viability of electric cars. We highlight one: the EU Battery Directive forbids the dumping of batteries in landfill; all must be recycled. Infrastructure for recycling Li-ion batteries on a large scale does not yet exist (3% of Lithium-ion batteries are at present recycled[13]).

The "Search" facility in the Sustainability database using "Cars" as a search term retrieves legislation relating to private vehicles. It also brings up records for materials used in cars and much else.

Economics[14]. Batteries for electric cars are still very expensive – as much as $10,000 to $15,000[15], or one third of the price of the vehicle –and can provide only limited range. The price of Lithium-ion batteries fell during the 1990s but flattened out at about $600 per kWhr. With fuel at $4/gallon (~$1/liter) in the US and about $1.8/liter in Europe, the economics of electric cars looks unattractive. However a 2012 analysis carried out by McKinsey & Co[16] predicts that the price for lithium-ion batteries could fall by as much as two-thirds by 2020, down to around $200 per kilowatt-hour. This, coupled with rising fuel price, might tip the balance.

A current economic concern is the investment in recharging points: providers are waiting for the number of electric car drivers to rise but drivers are waiting the number of stations to rise. Some governments are willing to subsidize charging points, but mainly in the cities.

The "Nations of the World" data-table of the Sustainability Database contains data for the current price of Lithium and that of gasoline, diesel fuel and electrical power (both domestic and commercial).

13 Telens Peiro, L. Villalba Mendez, G. and Ayres, R.U. (2013) "Lithium: sources, production, uses and recovery outlook" JOM Vol 65, pp. 896 – 996.
14 The Washinton Post, April 2, 2013. http://www.washingtonpost.com
15 The Wall Street Journal, April 17, 2012. http://online.wsj.com/article/SB10001424052702304432704577350052534072994.html
16 McKinsey July 2012. http://www.mckinsey.com/insights/energy_resources_materials/battery_technology_charges_ahead

Society. Automobiles give independence. Their manufacture creates employment. They also occupy space and, in conventional form, are responsible for noise and emissions. Secondary benefits of the electric car include reduction in noise and the ability to confine carbon release to power stations where it can be handled more effectively.

The cost, the limited range and absence of charging points for electric cars impedes their acceptance at present. Governments recognize these as problems and seek to reduce their impact by subsidies on EV purchase and installing and subsidizing charging points.

Electric cars are more expensive than ordinary ones. Affordability is an issue. The "Nations of the World" datatable of the Sustainability Database contains data GDP per capita and the median wage.

Summary of significant facts

- The supply-chain for neodymium and lithium is at present inadequate to support making 8 million electric cars per year.
- If charged from a national grid fed by gas or coal-fired power stations the carbon footprint of the car is at least 100 grams CO_2 /km.
- The weight and cost of batteries limits the range to less than 160 km per charge.
- Sales of electric cars at present depend on government subsidies of up to 20% of the price of the car.
- Legislation requires that 85% of the car, including the batteries be recycled. Facilities for recycling lithium-ion batteries and neodymium magnets is not, at present, in place.

Step 4: forming a judgment

What, then, is the likely impact of wide use of electric cars on the three Capitals? These are questions for debate, informed by the data generated by the Fact-finding step. Here is one view for discussion, summarized in Figure 3.

Natural Capital. Electric vehicles that use today's technology rely on a least two "critical" elements : Neodymium and Lithium. The analysis of demand created by EVs and the distribution of source-Nations for these elements was not reassuring: The projected demand for Neodymium for cars in 2020 is about half the current (2011) global production, most of it coming from a single Nation. Some of the demand in 2021 could be filled by recycling, not at present practiced. The design life of an electric car is of order 12 years. If the vehicles are leased, so that large groups of them are managed by a single enterprise, the recovery, reconditioning or recycling at end of life is straightforward. If they are sold, as cars are now, to individual purchasers then collection for recycling becomes more difficult but still manageable. A similar exploration for Lithium indicated a broader supply base but a demand in 2020 that exceeds current production capacity. These facts point to a technology that makes large demands on critical elements with inadequate supply.

Does the all-electric car achieve its Prime Objective, that of helping to de-carbonizing road transport? The carbon footprint of the electric car, if charged from the national grid of a typical Western nation, is roughly 100 grams per km. An increasing number of small IC driven cars already do better than this. We conclude that the Prime Objective is not achieved until the national grid is itself de-carbonized or an independent low-carbon source of electrical power is available. Neither appears achievable in the short (6 year) term.

Manufactured Capital. The aim of 8 million EVs per year by 2020, using today's technology, is achievable only if three conditions are met: the supply chain for the critical elements on which they depend is expanded and given a broader base; provision for recycling these elements is established; and grid-electricity generation capacity is increased.

Creating plant to build more than a million electric cars per year is a large investment in manufacturing technology. Is it a good investment? Some argue that it is not because, like wind-turbines, EVs are not competitive in cost without a government subsidy. As with all energy-using products the unknown is the price of hydrocarbon fuels over the next 20 years and the currently externalized cost of carbon-induced climate change.

Human Capital. A healthy manufacturing base makes a positive contribution to Human Capital: the jobs created by the automobile industry contribute to wealth and potentially to the well-being of the population of the nation in which they are built. But electric vehicles can contribute to human capital in this way only if they are widely accepted by the driving public. The limited range, at present, is an obstacle to acceptance.

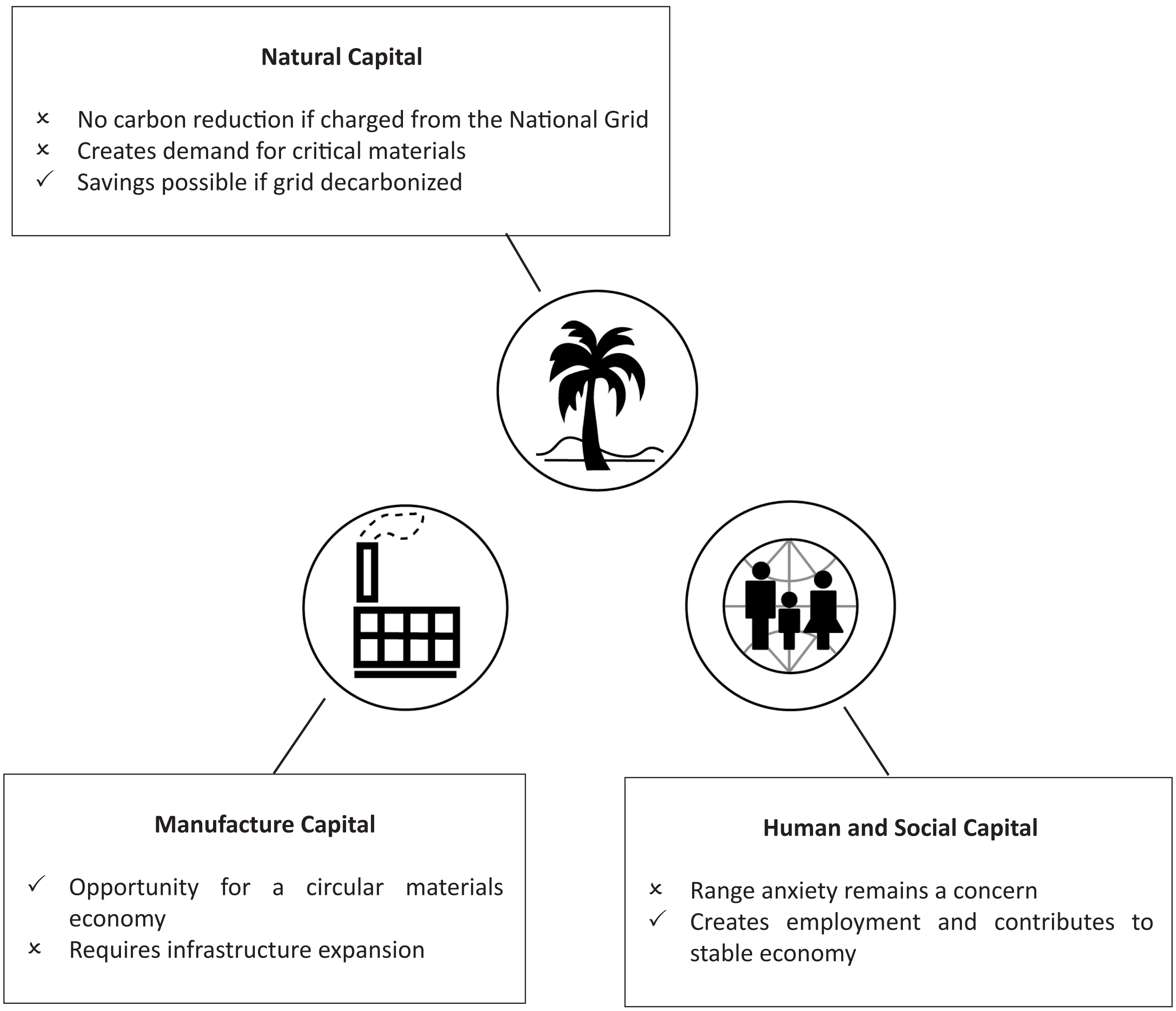

Figure 3. An overview of the impact of the findings on the three capitals.

Step 5: reflection

Short term. This is the moment to consider alternatives. Can the Prime Objective be achieved in the way assumed in the remit – by replacing petrol-driven cars by EVs that are used in the same way? It does not seem so. EVs cannot provide the range, convenience of refueling or (at present) the economy that consumers expect. Even more telling: charging EVs from the national grid of most nations carries a carbon footprint larger than that of many small IC and hybrid-powered cars today.

Long term. This is where the opportunity to expose innovation potential lies. To develop these alternatives further students might return to the "society" and "economics" dimensions and explore a the options and limitations for change in use and organization, thereby escaping the idea of an electric car as a simple substitute for one with and internal combustion engine.

Electric cars are good for short journeys. Could the public be re-educated to think of electric cars in a new way, not as a simple replacement for an IC engine car but as a vehicle well-adapted for urban use, when range is less important? Could it be made attractive to own a small electric car for daily commuting and rent a larger IC car for longer journeys, vacations or employment that required one? Or could large companies provide electric cars and on-site charge-points for staff, subsidizing their commuting in a way that best used electric vehicles? A shift from private ownership to fleet ownership by municipalities, service providers and employers with provision of recharging points at supermarkets, car-parks and place of work could make better use of the strengths of electric transport.

A central issue for electric transport is that of energy density. Suppose we accept that transport is best powered by high energy-density fuels with which batteries cannot compete. Technology exists for synthesizing hydrocarbons from CO_2. Rather than using electrical power to charge batteries, could it be used to synthesize methanol or ethanol to drive efficient IC-powered cars? The infra-structure for fuel distribution and maintenance already exits, and by drawing the CO_2 from industries that emit it such as power-stations, or cement works or from the atmosphere, true carbon-neutrality might be possible.

Electric vehicles can perform another, quite different function, that of making intermittent renewable energy from wind and solar sources more practical. Most cars are in use for less than 4% of the average day. Electric vehicles can then be charged during off-peak hours at cheaper rates while helping to absorb excess night time generation. The excess rechargeable battery capacity can then provide power to the electric grid in response to peak load demands. The vehicles serve as a distributed battery storage system to buffer power.

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