Case study: Electric buses[1]

Contents

The arguments for and against electric buses would, you might think, be very like those for and against electric cars, but this is not so. The objectives, size scales and time scales all differ. Comparing this case study with that for electric cars illustrates the point.

**http://www3.volvo.com/investors/finrep/sr13/en/rethinkingtransport/cleanersolutions/electromobility/fullyelectricbuses/fully-electric-buse.html*

[1] A set of PowerPoint frames illustrating this case study can be downloaded from www.grantadesign.com/education

Electric buses – Handout

Introduction

Emissions from vehicles in large cities regularly reach levels that are harmful to health. The oxides of nitrogen (NO_x) in particular are thought to be responsible for 4,000 premature deaths per year in London alone, where NOx levels frequently exceed EU guidelines. Diesel-powered buses are one of the culprits. By contrast, fully electric vehicles emit no particulate matter, oxides of nitrogen or carbon dioxide during use and are relatively quiet, making them attractive for use in densely-populated urban environments. This case study investigates the economic and environmental consequences of replacing diesel by electric buses on a city scale, taking London (England) as an example.

The proposal

The electric vehicle (EV) industry is growing. The annual production of EVs in 2014 reached 320,000 units, bringing the total global market up to 740,000 vehicles[2]. Electric buses, however, have not expanded as fast. In 2015, BYD, the leader of electric vehicles and electric buses, sold about 6,000 of these buses worldwide[3]. To meet emissions targets, the city of London has focused on the transportation sector, which accounts for 20% of London's vehicle-based emissions. Buses make up 5% of the transport total[4]. The aim: to reduce NO_x emissions in London by replacing diesel buses with battery-powered electric buses.

Is this a sustainable solution for public transport in London? Are electric buses really environmentally friendly? Are they economically feasible? These questions are the subject of this case study.

Background information.

- The cost of a battery-powered electric bus ranges from 400,000 to 600,000 GBP per unit[5]. A diesel bus costs about 260,000 GBP per unit.
- Today's electric buses on average have 180 kWh capacity batteries and a claimed range of more than 150 miles (250 km) between charges[6].

The steps

- 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 the three capitals?
- Is the proposal a sustainable development? Could the objective be met in other ways?

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[2] Ayre, J., 2015. *Clean Technia.* http://cleantechnica.com/2015/03/28/ev-demand-growing-global-market-hits-740000-units/ [Accessed 7 September 2016].
[3] Bloomberg News, 2015. *Bloomberg.* http://www.bloomberg.com/news/articles/2015-10-15/byd-said-to-expand-u-k-bus-production-seek-new-europe-factory-ifrmy6av [Accessed 7 September 2016].
[4] Rencken, C., 2016. *Focus on Transport and Logistics.* http://www.focusontransport.co.za/regulars/focus-on-bus-and-coach/bus-and-coach/2902-green-buses-gaining-ground.html [Accessed 7 September 2016].
[5] Cooney, G. A., 2011. *Life Cycle Assessment of Diesel and Electric Public Transportation Buses ,* Pittsburgh: University of Pittsburgh.
[6] BYD (2016) http://www.byd.com/la/auto/ebus.html

Where can CES EduPack Sustainable Development Edition help with Fact-finding?

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

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

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

The **Power Systems – Energy storage data-table** has data for battery types and their characteristics.

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

The **Graph facility** of the **CES EduPack software** allows data to be plotted, annotated and saved to WORD documents.

Electric buses – example of assessment

The numbering of the sections corresponds to that of the 5 steps of the analysis. The CES EduPack Sustainability Database helps with fact-finding in ways described in the Handout for this Case Study

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

- ***Objective:*** Reduction of inner-city NOx emissions of London's bus fleet buy replacing diesel by electric buses
- ***Size scale***: There are 8,600 buses on London streets.
- ***Time scale***: by 2020.
- ***Functional unit:*** NOx per passenger-km.

These immediately poses some critical questions:

- What is the replacement going to cost? Is it affordable? Will it drive up fares?
- What materials are used in electric buses that are not used in today's conventional buses? Today's EVs use lithium-ion batteries to drive compact, permanent-magnet DC electric motors; the motors use neodymium-boron magnets. Are the supply chains for lithium and neodymium sufficiently robust to ensure delivery of 8,600 electric buses?
- 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 the London's bus fleet?

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

Step 2. Stakeholders and their concerns.

The stakeholders fall into three groups: the government, the industry and the public.

- Government bodies: the European Union (EU), the UK Department of Transportation and Transportation for London (the London planning authority)
- Industrial bodies: bus makers, battery makers and, to a lesser extent, oil and electricity producers
- Public: Bus operators and passengers, green activists, London residents

Headlines from around the UK underpin the hype surrounding the public versus electric bus debate.

- *"30,000 deaths in the UK were linked to air pollution in 2008 – with 4,000 in London alone."* (Parliamentary Business, from the Commons Select Committee, 2011).
- *"UK given final warning over London air quality."* The UK receives a written warning by the European Union to clean up London's air or face fines of up to 300m GBP (The Guardian, 3 June, 2010)
- *"On average our measured road test NOx emissions from Euro 5 vehicles were 1135 mg/km - over six times higher than the 180 mg/km official legislative NEDC laboratory test limit".* (UK Secretary of State for Transport, June 2016.
- *"London bus companies 'exploit loophole' to run high-emission vehicles."* Bus operators were accused of using older, high emission buses because they cost less (The Evening Standard, 12 February, 2015).

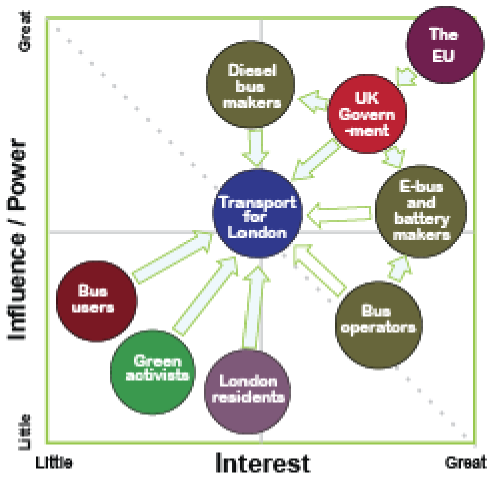


Figure 1. Stakeholder interest and influence

Stakeholders	Concerns
DfT (Department for Transportation)	To meet mandatory European air quality targets
TfL (Transport for London)	Reduce environmental impact of London's bus fleets without breaking the budget. Emphasis on low cost and quick mass transport.
City of London administration	Cost effective way to cut NOx emissions to avoid EU air quality requirements
Makers of diesel buses	Retaining market share in the transportation sector in face of disruptive technology. Legislation limiting diesel emissions in cities.
Makers of E-bus	Capturing market share from diesel bus-makers. Security of supply of materials essential for e-bus technology, including rare earths.
Battery makers	Security of supply chains for raw materials of batteries, which include lithium.
Bus operators	Range, battery life, replacement cost, and safety of electric buses
Bus passengers	Unit journey costs, reliability, safety.
Green activists	Reducing the damaging impact of gasoline and diesel powered vehicles on the environment.
Londoners	The health hazards posed by NOx emissions

Are these concerns valid or, if they are not, can they be refuted? That is the task for the next step 3, Fact-finding.

Step 3: Fact finding

What additional facts do we need for a rational discussion of the Prime Objective – that of reducing NO_x emissions emitted by London buses to zero. This is addressed below.

Materials

The energy density in even the best batteries is far lower than that in diesel fuel (Figure 2). Lithium-iron (LiFePO4) batteries are at present the choice for large capacity, high power applications such as electric cars, electric buses and fork-lift trucks[7]. The energy density of lithium-ion batteries is 110 kW.hr/kg[8], meaning that a 200kW.hr battery (giving a potential range of 150 miles) weighs almost 2000 kg. The Li-ion battery can be used beyond the life of the bus such for domestic energy storage, but it remains a major cost driver of purely electric vehicles: materials constitute 75% of the cost of Li-ion batteries[9].

[7] PowerStream, 2016. *PowerStream.* http://www.powerstream.com/ [Accessed 7 September 2016].
[8] Majeau-Bettez, G. H. T. R. &. S. A. H., (2011). Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-in Hybrid and Battery Electric Vehicles.. *Environmental Science & Technology,* 45(10), p. 10.
[9] http://www.anl.gov/energy-systems/publication/costs-lithium-ion-batteries-vehicles

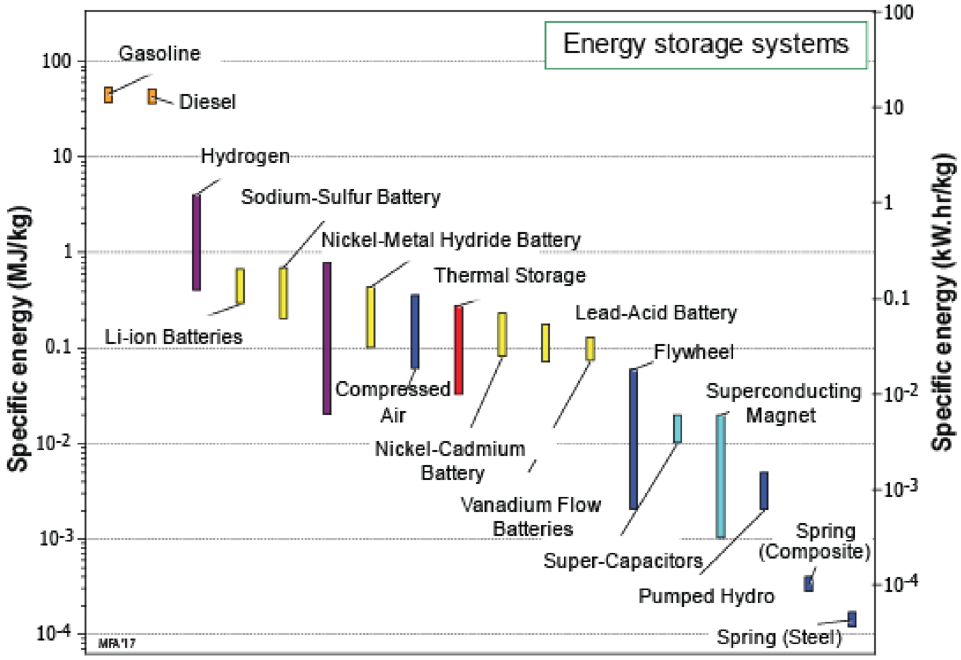


Figure 2. The energy density of energy storage systems. Lead-acid, Nickel-metal hydride, Lithium ion and Flywheels have all been used in buses (source CES EduPack).

Most electric buses today use lithium-ion batteries. A 200 kW.hr battery contains about 90 kg of lithium, so replacing all 8,600 buses at present circulating in central London with electric vehicles with a life of 10 years creates a demand for lithium of 77 tonnes per year, trivial in comparison with the annual production of 34,000 tonnes per year – though if the replacement were adopted by other large cities, supply would be stretched.

Table 1 Lithium producing nations, 2012

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	**34,000**

Critical materials. Nations draw up list of materials that are seen as vital for the economy of the country and for which the supply chain may by uncertain[10]. Lithium does not appear on the EU critical list but very little lithium is produced in Europe (Table 1), where it is ranked as a material of importance to the economy. Thus, a particular concern Is the lack of a recycling infrastructure for lithium-ion batteries: only 3% are recycled at present[11] .

Table 2 Rare earth producing nations

Rare Earth producing nation	Tonnes/year 2011
China	130,000
India	3,000
Brazil	550
Malaysia	30
World	**133,580**

By contrast rare earth elements, used in the DC motors that power electric vehicles, rank high on the EU critical list. An EV such as the Nissan Leaf has a rated power of 80 kW delivered by DC motors containing magnets weighing roughly 12 kg. A BYD electric bus is rated at 180 kW[12] so we anticipate a magnet content is around 30 kgs. These magnets contains neodymium (23%) and dysprosium (4%), both elements with extreme supply-chain concentration (Table 2) and,

[10] European Commission, 2014. *Report on Critical Raw Materials for the EU,* Brussels: DG Enterprise.
[11] Telens Peiro, L. V. M. a. A. R., (2013). Lithium: sources, production, uses and recovery outlook. *Journal of Metallurgy,* Volume 65, pp. 896-996.
[12] BYD (2016) http://www.byd.com/la/auto/ebus.html

additionally, subject to the "balance problem." The balance problem refers to the imbalance of demand for the different rare earth elements[13]. Rare earths occur as mixed ores and are mined together, so extracting one means separating it from all the others. To compensate for the cost of processing and stockpiling the unwanted elements, the prices for those that are in demand increases.

Today only about 1% of all rare earths is recycled[14]. With increasing demand for EVs and wind turbines, the need for a recycling infrastructure is pressing.

The Materials data-table in the Sustainable Development Edition of CES EduPack contains records for lithium and rare earths from which the data plotted in Figure 2 and listed in Tables 1 and 2 were drawn.

Environment

Road transport accounts for more than one third of all emissions to air in the UK, exceeding that from the power sector and that from industry[15]. Diesel power emits less greenhouse gases (CO_2, CO and CH_4) than gasoline (upper part of Figure 3), resulting in pressure to switch of diesel in the 1990s. More recently, however, diesel has been identified as a particular emitter of the NO_x (lower part of Figure 3). This has led the Mayor of London to consider an entry charge or even a complete ban on diesel vehicles entering London. The move to electric buses is motivated by the same aims.

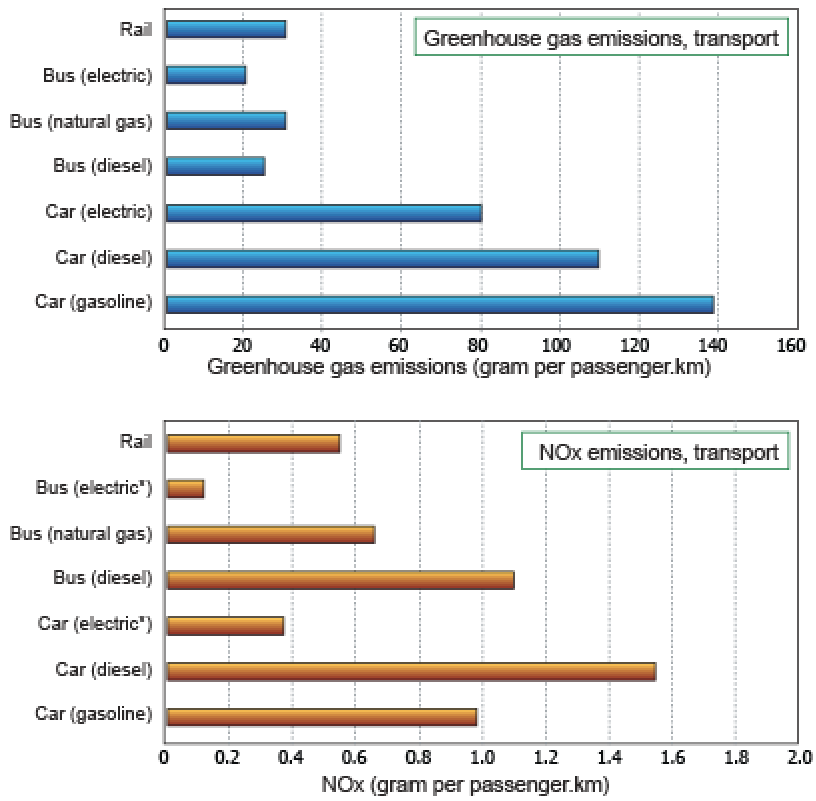


Figure 3. Greenhouse gas and NOx emissions for transport systems, 2014
(* based on US power-station average of 1.2 g NOx per kW.hr)

[13] Binnemans, K., 2014. *Economics of Rare Earths: The Balance Problem.* Milos, European Rare Earth Resources Conference.
[14] Binnemans, K., 2013. Recycling of rare earths: a critical review. *Journal of Cleaner Production,* Volume 51, pp. 1-22.
[15] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/486085/Emissions_of_air_pollutants_statistical_release_2015_-_Final__2_.pdf

Most electric vehicles are charged using power from the National grid. Many of the the power stations producing it are fueled with coal, oil or gas, and therefore have emissions of their own. A recent study[16] suggests that fuel-efficient conventional vehicles are just as eco-friendly as battery powered vehicles. On a national scale this may be significant, but the inner-city problem is a local one: it is the tail-pipe emissions that cause the damage, and here electric vehicles excel.

The Eco Audit Tool of CES EduPack contains data for the energy mix in the nations of the world allowing the carbon footprint associated with the use of energy in a given nation to be included in the audit.

Legislation and Regulation

Legislation limiting emissions of the oxides of nitrogen (NO_x) exists worldwide. NO_2 is one of the thirteen substances targeted in the Ambient Air Quality Framework Directive[17] , imposing a limit of 40 μg/m^3 in the atmosphere. Section 302 of the US Extremely Hazardous Substances Act imposes similar limits. Current levels of atmospheric NO_x in London frequently exceed this limit.

The European Union End-of-Life Vehicles Directive (ELV)[18] mandates that 80% of all vehicles must, at the end of life, be recycled, but this Directive does not apply to buses. The EU Battery Directive, however, prohibits sending batteries of any sort to landfill, essentially requiring that they be recycled. As mentioned under "Materials", a recycling infrastructure for lithium-ion batteries is not yet it place.

The Legislation data-table in CES EduPack lists some of the regulations affecting Nitrogen Dioxide or Nitrous Oxide around the world.

Society

Air pollution damages health and reduces the quality of life. It is now realized that NO_x emissions are particularly damaging. The damage depends on where the emissions are released. Those from power stations are far from city centers, are localized and can be controlled at source. Those from transport are distributed, harder to control and particularly concentrated in city centers.

Air quality economic analysis is a developing economic tool to guide national policies on emission controls. The UK Department for Environment, Food and Rural Affairs (DEFRA) publishes their estimates of the damage costs of NOx emissions. Table 2 shows some of DEFRA's data. Not surprisingly, the uncertainties are large – take it to be $\pm$ 30% – but that hardly matters when the differences are as great as this. The ball-park cost of NOx in central London is 120,000 GBP per tonne. It's a useful number because it allows a more realistic economic assessment of electric buses. That comes next.

Table 2. Damage costs of NOx emissions by source and location in the UK[19].

Source and location	Estimated cost GBP/tonne NOx, $\pm$ 30%
Energy Supply Industry (ESI)	1,200
Industry	13,100
Domestic	14,600
Transport average	25,300
Transport outer London	77,526
Transport inner London	118,688

[16] Hawkins, T. R., 2012. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology,* 17(1), pp. 158-160.
[17] Council of the European Union, 1996. *Air Quality Framework Directive.* Brussels: s.n.
[18] European Parliament, 2000. *DIRECTIVE 2000/53/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL.* Brussels: European Parliament and Council of the European Union.
[19] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/460398/air-quality-econanalysis-damagecost.pdf

Economics

Electric buses cost more than the diesel equivalent but their fuel cost is less[20]. The base price of a diesel bus is 262,955 GBP; that of an electric bus tops out at 510,884 GBP, nearly twice as much. A London bus covers about 70,000 km per year at a fuel efficiency of 35 liters per 100 km. Diesel fuel in the UK costs 1.2 GBP per liter, so the fuel cost is 29,400 GBP per year. An electric bus consumes about 1.6 kW.hr per km. If an electric bus driven over the same distance using electrical power at 0.13 GBP per kW.hr the fuel cost is 14,600 per year.

The old RouteMaster London bus emitted 9g NOx/km, and thus 0.6 tonnes of NOx per year, all of it in inner London. The associated health cost is 71,000 GBD per year. The electric bus emits none. If the capital cost of the bus is written off over 10 years, the totals become

Diesel bus: 26,300 + 29,400 + 71,000 = 126,000 GBP per year

Electric bus: 51,100 + 14,600 = 65,000 GBP per year

It is claimed that the new Euro VI model hybrid bus now replacing some of the older London buses emits only 0.2g NOx/km. The health cost then falls to 1,670 GBP per year and the cost of the diesel falls below that of the electric equivalent.

Summary of significant facts

- The cost of gasoline and diesel is still too low to make the switch to electric buses.
- Traditional diesel buses do not contain any geopolitically risky or price volatile materials, whereas electric buses depend more heavily on materials for which the supply chain is uncertain.
- The range anxiety experienced by those weary of electric vehicles is not necessarily replicated with electric buses in London. This is due to their short distances travelled and their frequent rest stops made throughout the day, where recharging can be arranged.
- NOx emissions in London must be brought down to the allowable limit.
- Public bus is one of the greenest forms of mass transit, but could be greener if the grid was decarburized.
- The price of electric buses does not outweigh the damage costs of NOx emissions, but if damage costs from CO2 emissions were also considered then this might make the hefty price of e-buses worth it.

Step 4: Forming a judgement

What, then, is the likely impact of wide use of electric cars on the three capitals? These are questions for debate, informed by the research conducted in the fact-finding step. The results are summarized in Figure 4.

Natural Capital

Does an all-electric bus fleet achieve its Prime Objective of reducing inner-city NOx emissions? Buses account for 20% of central London NOx emissions. Replacing the current diesel fleet by e-buses reduces these emissions by 20% with significant, quantifiable, health benefits. Emissions are, of course, associated with electric power generation but these are at the power station where it is easier to deal with them.

[20] http://www.eprg.group.cam.ac.uk/wp-content/uploads/2013/01/EEJan13_EconomicsEVs.pdf

Manufactured Capital

Electric buses are expensive. They are cheaper to run but this is alone does not make the switch from diesel to electric financially attractive. If, however, the cost of damage to health, estimated at 120,000 GBP per tonne of NOx, is included, the electric option becomes comparable to the diesel alternative. The associated reduction in emissions of particulates brings further health-cost savings. An obvious difficulty in folding health costs into the overall cost estimate is that transport and health are financed via separate authorities and budgets.

Electric buses today rely on at least two “difficult” elements: Neodymium and Lithium. Neodymium is listed as “critical “ because of uncertainty of its supply, whereas concern for lithium comes from high price and demand, both of which make buyers and suppliers uncomfortable. Building a recycling infrastructure for both elements, at present absent, can mitigate this problem.

Human Capital

The ultimate social benefit of reducing NOx emissions is Increase in life expectancy. Transport is a social need so increasing the ways to do it in an environmentally friendly way is also enhancing human health and well-being. Mass transport reduces traffic, congestion and the need for parking space all of which damage human capital. The range anxiety, a concern issue electric cars, is not an issue with electric buses that have regular timetables with scheduled recharging.

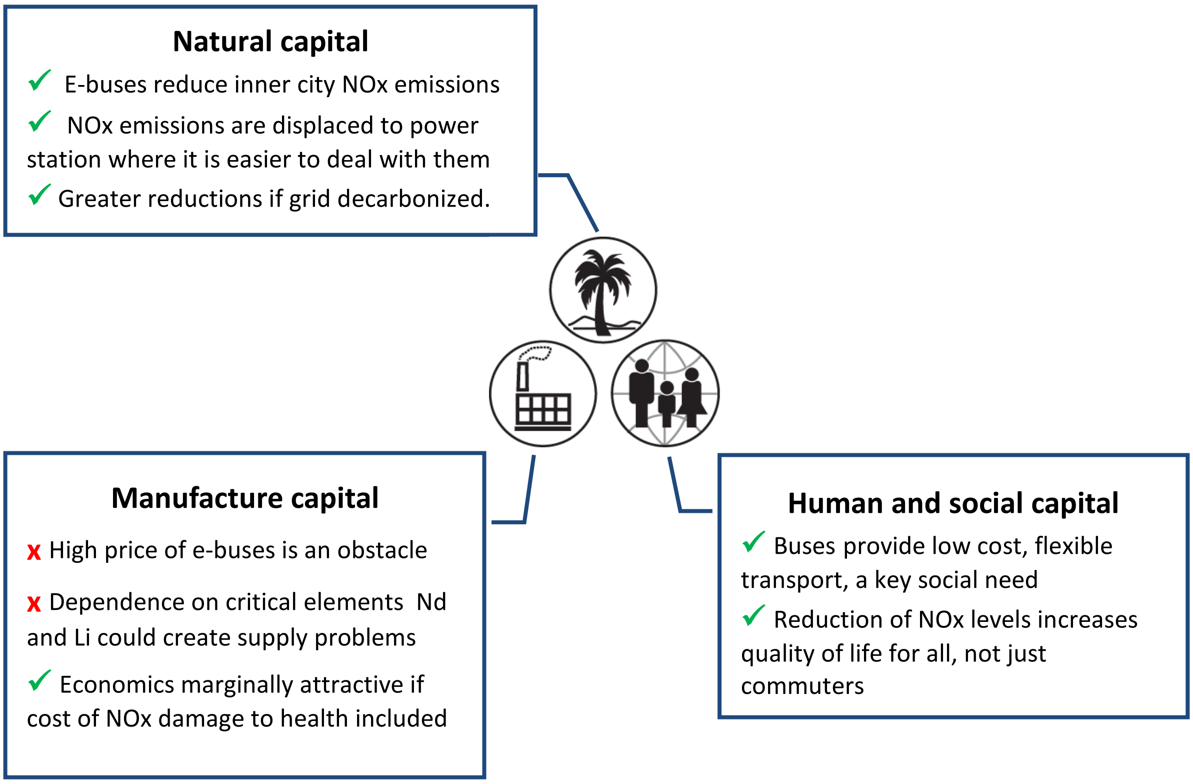


Figure 4. The impact of the findings on the three capitals.

Step 5: Reflection

This is the moment to consider alternatives.

Short term. At first sight a change to electric buses does not seem financially attractive. Can the high capital investment made in electric buses be paid off by the reduction of damage costs of NOx emissions? That may be possible where the health costs are highest, but even then the secondary costs of a whole-sale move to electric buses (setting up a charging infrastructure, a revision of timetables etc.) tips the balance against them. Unless the price decreases or if governments provide subsidies to incentivize their purchase, they will not be an economically viable option in the short term.

Long term. This where the opportunity to expose innovation potential lies. To develop these alternatives it is worth re-examining the "society" and "economics" dimensions. A fuller estimate of the monetary value of emission-reduction – not just NOx but also CO_2 and particulates, might be enough to justify investing in e-buses. Developing a secondary market for used Li-ion batteries for domestic energy storage, for instance, allows the capital investment to be shared among multiple parties.

Since electric buses contain larger amounts of Li and Nd than electric vehicles, governments might be more motivated to invest in a recycling infrastructure for these to keep them in the EU and make their continued supply less uncertain.

Further case studies.

Hydrogen and biofuels/biogas for HGVs. Deployment of hydrogen fuel cells in buses offers a stepping stone to potential deployment in for heavy, long distance goods vehicles in the longer term. While currently there are a number of challenges, it is plausible that these could be addressed, at least for some applications, given ongoing research and investment. Should these types of buses offer a solution, even with the use of limited bioenergy resources here in terms of greater emissions reduction potential?

Appendix

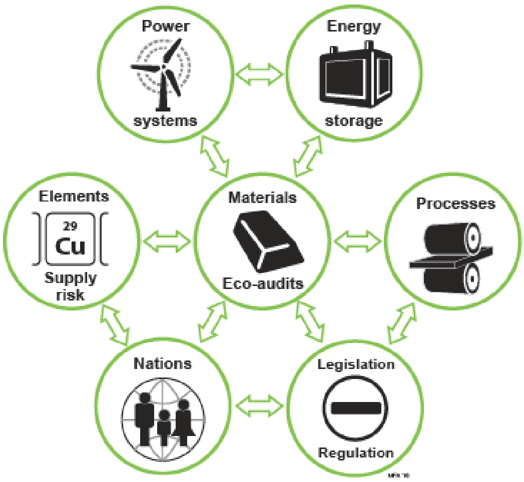
At first sight the case for electric buses looks very like that for electric cars (see among the case studies on the Granta's Teaching Resources Website) – but the reality is different. The table explains the differences

Characteristic	***Private electric car***	***Electric inner-city bus***
Weight when loaded kg	*1,500*	*19,000*
Engine power, kW	*30*	*180*
Top speed, km/hr (mph)	*160 (100)*	*74 (45)*
Battery capacity, kW.hr	*24*	*340*
Range on single charge, km (m)	*160*	*200*
Typical use time per year, hr	*300*	*2,600*
Typical distance driven per year, km (miles)	*17,000 (10,000)*	*52,000 (32,000)*
Average speed km/hr (mph)	70 (42)	*20 (12)*
Maximum seating capacity.	*5*	*40*
Price per vehicle	*$ 20,000*	*$ 500,000*

Sustainable Development Teaching Resources

Resources

- *Granta Teaching Resource Package: Active-Learning Tool Kit – Sustainable Development*
- *PowerPoint presentations*
- *Explanatory handouts*
- *Templates*
- *Micro-projects*



Case studies

- *Greener beer cans*
- *Bioplastic or polyprop?*
- *Electric cars*
- *Electric buses*
- *Which hand dryer?*
- *Plastic books*
- *Wind farms*
- *Low carbon concrete*

The CES EduPack Sustainable Development Edition

The Sustainability Database is a fact-finding tool to introduce students to the complexity of decision-making for sustainability. It helps contextualize the role of materials and it expands competences in critical thinking about complex issues (including resource use, legal barriers, ethical considerations, societal and economic concerns). The individual data-tables are explained in Section 3 of this Teaching Resource Package.

The book "Materials and Sustainable Development" (ISBN-13: 978-0081001769) describes this method and its applications in more detail.

Authors. Professor Mike Ashby and Education Division team at Granta Design Ltd. www.grantadesign.com/education (with the support of Gwen Bailey, who did the internship at Granta in August/September 2016).