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# Environmental impact of Converted Electrical Motorcycle

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## Abstract

This study explores the environmental impact of the conversion of an internal combustion engine (ICE) sports motorcycle into a converted battery-powered electric vehicle (CBEV). Zero tailpipe emissions might lead to the assumption that such an ICE-to-BEV conversion will always yield net positive environmental benefits in life cycle greenhouse gas (GHG) emissions and energy reductions, but energy inputs and materials impacts associated with the conversion of a CBEV are weighed against savings during post-conversion usage. It was found that conversion would reduce the life cycle energy consumed and emissions produced of a typical motorcycle by 72% and 45% respectively. These findings have important considerations for the current global transportation landscape.

*Keywords: emissions, energy, LCA (Life Cycle Assessment), motorcycle, student project*

## 1 Introduction

Plagued by triple threats of energy security, climate change and soaring crude oil prices, the global transportation industry is currently in an unenviable position. Given that transport accounted for 13% of global GHG emissions [1] and over half of global oil consumption in 2012 [2], the industry is sandwiched between the above challenges and its role as an integral engine of the global economy.

It is against this backdrop that electric vehicles (EVs) have made their foray into automotive markets around the world. EV manufacturers make liberal promises of environmental friendliness (Tesla's *Zero Emissions. Zero Compromises.* and Nissan Leaf's *100% electric. Zero gas. Zero tailpipe.* are just two examples) but numerous studies have shown that EVs only pay off the emissions and energy debt they incur in manufacturing processes when paired with a relatively green electricity grid and emissions controls at power generation plants [3]. Decision makers have hence turned to life cycle assessments (LCA) of transportation fuels for inputs in public policies on transportation, giving rise to a correspondingly growing wealth of literature on the topic [4 – 7].

This LCA study examines a conversion project on an ICE motorcycle, comparing the energy consumed and greenhouse gas emissions embodied in the conversion materials against the use phase savings the CBEV is expected to reap, relative to the pre-conversion ICEV.

## 2 Definition of Goal and Scope

### 2.1 Goal

The goal of this LCA is to (1) compile, quantify and evaluate the environmental impact of the conversion of an ICE motorcycle, and (2) identify main impacts of the conversion as starting points for targeted reduction strategies.

This will be a comparative LCA between an ICEV and a converted electric vehicle (CEV), that is, flows for the common components are ignored. For instance, the frame, motor and fenders for the original ICEV will have to be disposed of regardless whether it runs on petrol or electricity. The ICEV frame, as built, is a sunk cost that does not change with the conversion. It is hence disregarded to focus on the parts of the motorcycle which change before and after the conversion.

## 2.2 Scope

### 2.2.1 System Boundaries


Figure1: Life Cycle of ICEV parts

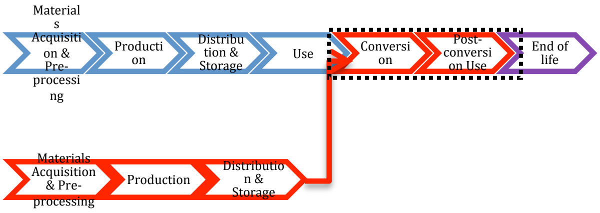


Figure2: Life Cycle of CEV composing ICEV parts and new EV parts. Black box indicates scope of study.

As seen in Figs. 1 and 2 above, conversion introduces 2 new stages of interest into a vehicle's traditional life cycle: conversion, and post-conversion usage (end of life processes are a complex mix of export and scrapping in Singapore's circumstances and have not been included in this iteration).

The product is a conventional ICE sports motorcycle, the Honda CBR400RR. The entire motorcycle has been defined to be the functional unit. Where applicable, each conversion component on the motorcycle is evaluated from extraction of raw materials to end of life processing, using the LCA databases GREET2.7, GEMIS4.8 and GaBi 5.0 Education.

### 2.2.2 Data Categories

In line with quantifying the major environmental impacts of the EV parts of the motorcycle, the following data categories were identified:

- Raw materials input
- Emissions to air and water

### 2.2.3 Data Quality Requirements

Data used came from directly weighing the components purchased, material composition estimates from Argonne National Laboratory's GREET2.7 model, PE International's Gabi 5.0 Education, GEMIS 4.8.1 and Tan's work [8] on the LCI inventory on electricity generation in Singapore.

# 3 Life Cycle Inventory Analysis

## 3.1 Production Phase

Data collection was done part by part:

- Lead acid batteries
- Motor
- Battery and motor mounts
- Control panel

The weight of each part is shown below:

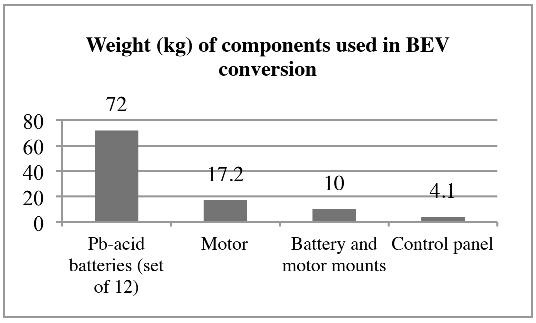


Figure3: Weight of components used in conversion

Fig. 3 shows a life cycle inventory of major components used in the conversion. It does not include, for instance, items such as the DC/ DC converter the team had to purchase to step down the electrical supply, nor the cables and insulation comprising the electrical circuit. The materials and their origins are then translated with a combination of GREET2.7, GEMIS 4.8 and Gabi Education LCA databases to generate an impact inventory, consisting of energy consumption, greenhouse gas emissions (gCH4, gN2O and gCO2 converted to gCO2e), and criteria air pollutants (CO, NOX, SO2).

2.1.1 LCA Data for Materials

2.1.2. Manufacturing

LCI data values (energy and emissions) were drawn from the LCA software GaBi 5.0 from PE International and GREE which was used. It included manufacturing data. An aggregate inventory for the major components of conversion is included in Table1 below.

Table1: Combined LCI for major components used in conversion

ENVIRONMENTAL IMPACT OF ALL MATERIALS

| | Motor | Batteries | Controller | Mount | Transportation | Total |
|---|---|---|---|---|---|---|
| **Energy Use: mmBtu** | | | | | | |
| **Total Energy** | 0.207156 | 2.92125 | 0.085186 | 0.286703 | | 3.500295 |
| **Fossil fuels** | 0.183448 | 2.911185 | 0.077237 | 0.203054 | | 3.374925 |
| **Coal** | 0.100984 | 0.09062 | 0.021358 | 0.145585 | | 0.358548 |
| **Natural gas** | 0.072362 | 0.330191 | 0.041859 | 0.037633 | | 0.482045 |
| **Petroleum** | 0.010102 | 2.490374 | 0.014021 | 0.019836 | | 2.534332 |
| **Total Emissions: grams** | | | | | | |
| **VOC** | 1.974061 | 39.43846 | 1.596755 | 4.134763 | | 47.14404 |
| **CO** | 13.00818 | 115.6903 | 5.671513 | 4.460582 | | 138.8306 |
| **NOx** | 20.59784 | 345.203 | 6.967304 | 24.1748 | | 396.943 |
| **PM10** | 22.57003 | 39.85459 | 7.517251 | 64.49065 | | 134.4325 |
| **PM2.5** | 7.004572 | 21.13261 | 2.871622 | 26.71504 | | 57.72385 |
| **SOx** | 43.80946 | 163.66 | 37.36077 | 66.86488 | | 311.6951 |
| **CH4** | 49.70338 | 394.4753 | 28.85703 | 41.26918 | | 514.3049 |
| **N2O** | 0.214818 | 5.220106 | 0.133266 | 0.23939 | | 5.807581 |
| **CO2** | 14817.5 | 225486.4 | 4806.047 | 19723.68 | 1238769.34 | 1503603 |
| **CO2 (VOC, CO, CO** | 14844.09 | 225791.1 | 4819.936 | 19743.58 | | 265198.7 |
| **GHGs** | 16150.77 | 237208.6 | 5669.219 | 22102.57 | | 281131.2 |
| **Urban Emissions: grams** | | | | | | |
| **VOC** | 0.119645 | 7.958026 | 0.037785 | 0.112424 | | 8.22788 |
| **CO** | 1.138747 | 8.327024 | 0.166005 | 0.665877 | | 10.29765 |
| **NOx** | 7.407941 | 23.30383 | 1.210138 | 7.179105 | | 39.10101 |
| **PM10** | 0.84252 | 4.532007 | 0.135364 | 0.779073 | | 6.288963 |
| **PM2.5** | 0.679891 | 2.774914 | 0.107004 | 0.611818 | | 4.173626 |
| **SOx** | 18.44188 | 23.14528 | 1.756221 | 1.586384 | | 44.92977 |

Assumptions made in this stage of data tabulation include (i) exclusion of smaller parts used during conversion such as cables, tools, resistors etc. (ii) zero values allocated to "others" [materials] for the electronic controller's and batteries' impact inventories and (iii) same material composition as provided by GREET 2.7 assumed.

For (ii), it was difficult to ascertain the nature of "other" materials used in the production of the batteries and controller, and these were hence omitted – possibly understating the environmental impact of the CBEV. For (iii), it was impossible for a study of this scale to determine the exact mass composition of the various materials actually used in our conversion – hence, estimates from the EV section of the GREET 2.7 database were used.

## 3.2 Use Phase

Table2: Comparison of energy usage and GWP during usage for ICEM and CEM

| ICEV | | | BEV | | |
|---|---|---|---|---|---|
| Vehicle Characterization | D/year (km) | 13400 | | D/year (km) | Vehicle Characterization |
| | D/mth (km) | 1117 | | D/mth (km) | |
| | Lifespan (years) | 8 | | Lifespan (years) | |
| | Fuel efficiency | 26 | - | - | |
| | Gas used (L) | 42.9615385 | - | - | |
| | Fuel density (kg/L) | 0.991 | | | |
| Fuel content | E content (kWh/L) | 9 | - | - | |
| | E used (kWh) | 386.653846 | 29.43 | Monthly cost (S$) | |
| | **E used (MJ)** | **1391.95385** | 0.2628 | E price (S$/kWh) | |
| | GWP of fuel (gCO2e/L) | 2311.7 | 111.986301 | E used/mth (kWh) | |
| | **GWP (gCO2e)** | **99314.1885** | - | - | - |
| Fuel upstream | Fuel production EI (MJ/t) | 1190 | 10.89 | OFST EI (MJ/kWh) | Fuel & infrastructure upstream |
| | Literature Fuel T&D EI (MJ/kWh) | 0.185 | 854 | OFST emissions intensity (gCO2e/kWh) | |
| | Fuel T&D EI (MJ/t) | 2369.295 | 0.179982 | OFST % contribution | |
| | Literature Fuel refining EI (MJ/barrel) | 882 | 7.79 | NGCC EI (MJ/kWh) | |
| | Fuel refining EI (MJ/t) | 5597.99506 | 473 | NGCC emissions intensity (gCO2e/kWh) | |
| | Fuel upstream total EI (MJ/t) | 9157.29006 | 0.779922 | NGCC % contribution | |
| | Tons used (t) | 0.04257488 | 2.91 | Solar PV EI (MJ/kWh) | |
| | E used (kWh) | 545.256547 | 217 | Solar PV emissions intensity (gCO2e/kWh) | |
| | Literature hidden primary E use (MJ/kWh) | 0.966 | 0.0001 | Solar PV % contribution | |
| | Literature hidden emissions intensity (gCO2E/kWh) | 97 | - | - | |
| | Actual hidden primary E use (MJ/kWh) | 0.71502226 | 8.03588736 | Weighted EI (MJ/kWh) | |
| | Actual hidden emissions intensity (gCO2e/kWh) | 71.7983012 | 522.629434 | Weighted emissions intensity (gCO2e/kWh) | |
| 1 month comparison | Total E used/mth (MJ) | 3354.87742 | 899.909304 | Total E used/mth (MJ) | 1 month comparison |
| | Total GWP (gCO2e) | 138462.682 | 58527.3373 | Total GWP(gCO2e) | |

| Fill color legend | Conversion factors | | Source |
|---|---|---|---|
| Literature value | kg/t | 1000 | - |
| Low uncertainty | kWh/t | 12807 | Carbon Trust, 2013 |
| Medium uncertainty | MJ/kWh | 3.6 | - |
| High uncertainty | mth/8y | 96 | - |
| | MJ/GJ | 0.001 | - |
| | t/kg | 0.001 | - |
| | L/barrel | 158.9872949 | - |

| Abbreviations | |
|---|---|
| E | Energy |
| EI | Energy intensity, either in units of energy/mass or energy input/energy output |
| OFST | Oil-fired steam turbine |
| NGCC | Natural gas combined cycle |
| GWP | Global warming potential, commonly measured in gCO2e |
| gCO2e | a unit of global warming potential, used to denote the radiative forcing exerted by 1g of CO2 in the atmosphere |

Uncertainties denoted by the different color codes of boxes are associated with data clarity and approximations made in the course of data calculations. 8 years was chosen as the lifespan of the converted vehicle as it is a common length of warranty on PEV batteries [9] and the lifespan of an EV is closely associated with the lifespan of its batteries [10].

# 4 Environmental Impact Assessment

Table3: Summary of Life Cycle Energy and Emissions Reductions for BEV against ICEV

| | | |
|---|---|---|
| **Conversion** | | |
| Total Energy used (GJ) | 3.69281117 | |
| Total GWP produced (tCO2e) | 1.515175129 | Only incurred for CBEV |
| **Usage** | | |
| Monthly Energy usage difference (MJ) (ICEV-BEV) | 2454.968113 | CBEV uses 233.55GJ (72%) less energy than ICEV over 8y lifetime |
| Lifetime Energy usage difference (GJ) (ICEV-BEV) | 231.9841276 | |
| Lifetime Energy usage difference (%) | 72.02949705 | |
| Monthly GWP difference (kgCO2e) ICEV-BEV) | 79.935345 | CBEV produces 45tCO2e (45%) less emissions than ICEV over 8y lifetime |
| Lifetime GWP difference (tCO2e) (ICEV-BEV) | 6.158617991 | |
| Lifetime GWP difference (%) (ICEV-BEV) | 44.47854027 | |

For the conversion, 2.0189 mmBtu was put into the production of the essential materials used, equivalent to 2.12 GJ. This is approximately the energy produced by a third of a barrel (~159L) of crude oil.

During usage, the BEV uses 235.6 GJ less energy than an ICEV over its 8-year lifespan, and taking into account life cycle energy embodied in conversion components, these savings fall by less than 1% to 233.5 GJ. As can be seen, the energy consumed during conversion is small enough to be negligible when compared to usage phase – a welcome result as far as enacting public transportation policies encouraging conversion. The breakdown of energy embodied and emissions produced are included in the graphs below.

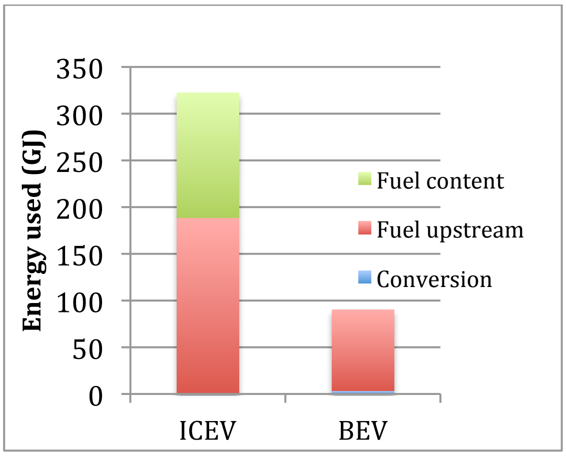


Figure4: Breakdown of ICEV/ Converted BEV energy usage

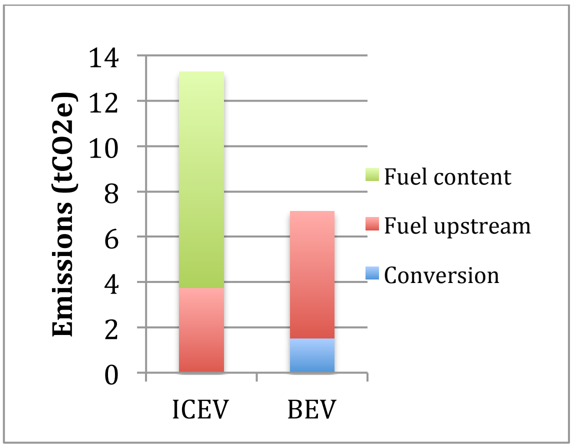


Figure5: Breakdown of ICEV/ Converted BEV emissions

As depicted in Fig. 4, it was found that the ICEV's upstream fuel processes account for slightly more than half (58.5%) of its energy used, while the embodied energy in the upstream fuel processes of Singapore's electricity mix of 78% natural gas, 18% fuel oil and 3% waste-to-energy. The latter dominate the CBEV's embodied energy from conversion onwards (95% of total). For greenhouse gas emissions as depicted in Fig. 5, the ICEV's fuel content is responsible for 72% of its emissions during its operational lifetime while upstream fuel processes continue to dominate the CBEV's aggregate emissions from conversion and usage.

Correspondingly, ICEVs also produce GHGs with higher global warming potential (GWP) than their BEV counterparts. This can be explained by looking at the energy usage and emission coefficients of energy in Fig.5: a BEV uses 112kWh per month while an ICEV uses a total of 931.85kWh (from direct petrol content and indirect petrol upstream processes), and the coefficients of emissions for ICEV are 2312gCO2e/kWh for petrol content and 71.8gCO2e/ kWh for petrol upstream processes. For BEV, the electrical emissions coefficients of 854gCO2e/kWh and 473gCO2e/kWh for oil-fired steam turbine and natural gas combined cycle electricity generation plants respectively are much lower. Combined with the lower energy usage of the EV, it would logically follow that emissions are much lower – GWP of BEV emissions are 58.5kgCO2e/mth, 45% lower than the 138.5kgCO2e/mth emitted by ICEVs.

As can be seen, usage phase of an ICEV dominates emissions, contributing 99.3kgCO2e, or 72% of an ICEV's total emissions of 138.5kgCO2e per month. For the same phase (fuel upstream), a BEV in Singapore is likely to receive 78% contribution from natural gas combined cycle power plants and 18% from oil-fired steam turbine power plants, hence the weighted energy and emissions intensity calibrated in the third and fourth last rows of the BEV columns.

From observation, the reason a CBEV wins out over an ICEV in terms of environmental impact are that (1) the grid in Singapore is relatively clean, (2) power plants in Singapore are relatively energy efficient, and (3) it is difficult to reduce the embodied energy and emissions produced from the petroleum consumed by the ICEV.

# 5 Discussion

From the LCA, we see that an electric motorcycle of the kind we converted is better for the environment than a typical motorcycle, using 232GJ, or 72% less energy from the time of conversion than a typical ICE motorcycle and producing 6.16 tons less CO2 equivalent of GHG (or 45% less) over its 8-year lifespan after conversion. As a basis of comparison, the average Singaporean had an annual carbon footprint of 6.4 tCO2 in 2009 [11]. From the equations used to calculate GHG emissions, it is easily seen that emissions for a CBEV would drop sharply for marginal increases of solar energy contribution to the national electrical grid, even taking into account the lifetime energy used and emissions produced in the manufacturing of PV cells.

## 5.1 Study Limitations

Freeware GEMIS, GaBi Education and GREET databases were used: Dutch and German databases that did not have the best energy and emissions coefficients for this part of the world. With more data and access to higher resolution data better approximations could be made, and be extended to the parts of the conversion ignored in this study: cables, tools purchased, sprockets etc. Greet and GEMIS were the main databases of choice, following their usage by 5 other LCA studies in Singapore on power and electricity generation (8, 12 – 15).

As environmental benefits (sum of GHG reductions and energy savings) are expected to diminish with time of conversion, further research can likely plot a graph of environmental benefits vs. time, in order to determine the point of time past which conversion on longer makes sense.

End of life processing can also be included in further studies: recycling of each part of a BEV is a new stage of the life cycle not seen in a traditional life cycle, and might also have bearing on the overall environmental impact of a converted electric motorcycle (although Singapore's lead acid battery recycling program makes gross increases unlikely).

Calculations made here were linear: they did not take into account the possibility of a changing grid for the BEV. It is very likely that the Singaporean electrical grid will be changing in the near future, with the recent establishment of an LNG terminal (with fuel coming from Australia, Egypt, Trinidad & Tobago, Nigeria and equatorial New Guinea) and a coal-fired power plant. These will indubitably change the emissions coefficients of the grid and hence affect the relative environmental performance of the BEV. Energy efficiency in engine optimization may also lead to improvements in the performance of the ICEV, just as engine wear and tear may gradually decrease the fuel efficiency of the ICEV, rendering it not just more fuel intensive but more emissions pollutive. If more data is made available, it would also be possible to take into account the deteriorating performances of ICEV and CBEV motors and batteries throughout their life cycle.

It would also be interesting to see the deviation of projected emissions of the Singapore electrical grid, as projected from the GREET database (from the sum of CO2, CH4 and N2O emissions per lb material used) vs. Kannan's more localized and hence more accurate figures (though his are provided just in terms of tCO2e/kWh). It would be an indicator of the accuracy of the other approximations made in this study.

## 5.2 Policy Recommendations

As of end 2010, 8,713 green vehicles were plying Singapore's roads (comprising full EVs, PHEVs, CNG and Bi-fuel (CNG/Petrol)) vehicles [16]. This represented a miniscule 0.94% out of a total of 921,958 cars in the same period. For years 2010 – 2012, between 30,000 and 36,000 vehicles have been de-registered [17] and either sent overseas for second-hand sales or scrapped. The use phase of such vehicles has been found to constitute the major part of their environmental impact, indicating that prolonging their useful lives would be a good inroad to mitigating this impact.

A major inhibitor to most people's choices between ICEV and BEV is cost; the necessity of government intervention to make BEVs cost-competitive has been highlighted by Chan [18] among others. Existing government schemes levying a premium on high-emission intensity vehicles can be extended to cover converted motorcycles – perhaps reducing the ARF or COE charges, or providing rebates on conversion to incentivize people to switch over. It is even conceivable to scrap the COE entirely, as the government can be ensured emissions from the converted vehicle will be cleaner, one of the original premises of having COEs.

Manufacturing lines would inevitably have our conversion team beat in terms of processes and decreasing marginal emissions and energy use. Our process, where each part is individually sourced from around the world, from places ranging from the United Kingdom to the United States and then transported to Singapore, is inevitably not as resource- efficient as it could be – another case for the mass deployment of conversion.

EVs also require 8 hours of charging for full charge and some riders may suffer from "range anxiety" for a given quantity of batteries. However, the high urban density in Singapore negates any need for long distance travel on a daily basis (for personal vehicles) – indeed, average annual kilometres travelled per private vehicle in 2011 was 52km per day. However, it is also the high density of living that will necessitate the provision of publicly available charging infrastructure for the successfully widespread adoption of EVs. Again, the government can step in here to provide these to the public, similar to the newly established charging station at City Square Mall.

Furthermore, EVs make more sense in Singapore than they might in other countries, because of our relatively clean energy mix: 78% natural gas from neighboring countries, 18% petroleum products such as fuel oil and diesel, and the remaining 4% a mix of biogas, waste-to-energy and solar energy. Additionally, the emissions will be better captured and cleaned at the power plants [19]. The "cleanliness" of the electrical grid has often been highlighted as one of the determining factors in whether EVs can indeed be claimed to be better during operational phase [3, 20].

# 6 Conclusion

In this study it was established that conversion would reduce the life cycle energy consumed and emissions produced of a typical motorcycle by 72% and 45% respectively. Both are important considerations for a nation of Singapore's circumstances, where over 95% of energy is imported and where clean air is a valuable premium that cannot be taken for granted.

Conversion would make sense to overcome the high upfront cost associated with purchasing brand new EVs; however, detailed consumer surveys such as the one the Energy Studies Institute is currently embarking on is necessary to establish consumer awareness of EVs (since EVs make up only ~1% of total vehicle population here), another determinant in the success of EVs.

Chester [7] recommended that infrastructure and supply chains be included in the life cycle environmental assessments of passenger transportation.

Singapore stands to reap great benefits from the successful mass deployment of EVs: it will be able to decouple its unceasing development wish from dependence on foreign oil and volatile oil markets, and it will further its attempts to decrease emissions.

In 2012, transportation accounted for 15% of fuel consumption – only behind industry [21]. To uphold its pledge of reducing emissions by 7-11% below 202 BAU levels as committed to the United Nations Framework on Climate Change, the transportation sector could be a good inroad for Singapore. Constant test-bedding and actively growing the EV industry here will also nurture new industries and technologies, establishing Singapore as a dynamic living lab in an up and coming industry.

# Acknowledgments

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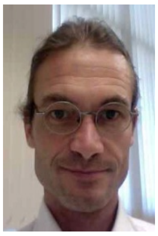

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