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Academic and corporate vehicle electrification research

Hans Pohl[1], Magnus Karlström[2]

[1]*Lindholmen Science Park, Box 8077, 402 78 Gothenburg, Sweden*

[2]*Chalmers Univ. of Technology, 412 96 Gothenburg, Sweden*

Summary

In this study, we develop and use a methodology to analyse scientific publications relating to vehicle electrification and associated key enabling technologies; batteries, fuel cells and electric machines with power electronics. The global research landscape is mapped, telling which countries and institutions that are most active and the impact of their research. China dominates in vehicle electrification research as well as in the enabling technologies and the trend is towards an even more dominating position. Automakers' electrification research activity is specifically studied. Vehicle electrification publications are rewarded with high citation impact and they include corporate actors to a high extent. General Motors is the automaker with the highest number of vehicle electrification publications during 2016 – 2020.

Keywords: BEV (battery electric vehicle), EV (electric vehicle), fuel cell vehicle, HEV (hybrid electric vehicle), research

1 Introduction

Electrified vehicles including batteries and fuel cells are on the market and the volumes are growing. This applies for cars, trucks and buses. But still, new solutions and knowledge are needed to broaden the market and reduce the environmental impact. This paper uses scientific publications to study knowledge development related to vehicle electrification.

Quantitative studies of vehicle electrification typically focus rather narrowly on electric vehicles and specific geographic areas. Through analysis of Scopus publications about electrified vehicles and key enabling technologies, this paper maps the global research landscape with a specific focus on academic-corporate collaboration. Which countries, universities and automakers are most active? What is their citation impact? How are they collaborating?

Following a brief review of previous publication studies of vehicle electrification, the methodology and data outlined. Thereafter, results are presented divided in two parts, one giving national data and one telling how automakers contribute with academic publications. Finally, discussions and conclusions follow.

2 Previous literature

Previous publication studies of vehicle electrification use a few keywords or classifications provided by the database supplier to identify relevant publications [1-7]. They focus on electric vehicles, which means publications explicitly mentioning both electrification and an automotive application, in some cases using search terms such as “electric vehicle” or similar [cf. 2 and 5]. Some studies try to gain a comprehensive view of electric vehicle technologies and understand the emphasis of current research. Web of Science dominates as the source of data.

The study of previous literature highlights some important aspects. First, it is important to have competence in vehicle electrification ***and*** scientometrics. Second, a clear description of the search strategy employed is critical for the interpretation of the results. And third, a narrow search extracting only “electric vehicle” publications, might miss important developments in the technologies enabling vehicle electrification.

3 Methodology and data

SciVal was used to extract and analyse Scopus publications. Scopus is the publication database with the broadest coverage [8]. Data was extracted in July 2021, which means that the last almost complete year was 2020. The identification of publications was based on queries. Queries use search terms which can be combined with AND, OR and AND NOT. In addition, entities such as countries, institutions and authors, were used. The identification of publications was based on queries. The search strategy is illustrated in Figure 1. Vehicle electrification publications, hereinafter called XEV publications, are the sum of “Vehicle electrification” and the overlapping areas joining the enabling technologies and the automotive domain (Figure 1 not to scale).

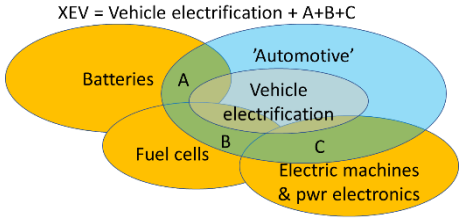

Figure 1: Search query for vehicle electrification publications (XEV)

One challenge is that publications in enabling technologies clearly relevant for vehicle electrification are seldom mentioning automotive applications in the title, keywords or abstract. Only a few percent of battery publications mention automotive applications. One of Sweden’s most productive battery researchers estimated that 50% of her publications addressed issues relevant for automotive applications. However, less than 3% were identified by the query for XEV publications. The strategy to manage this challenge was to include separate studies of publications in enabling technologies. The queries were designed in an iterative process, see Figure 2.

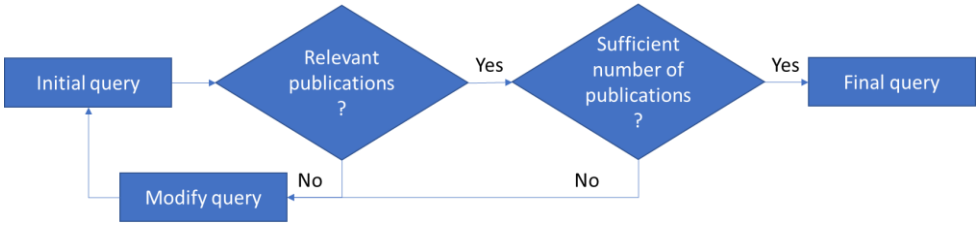

Figure 2: Query design process

A manual scrutiny of 100 randomly selected publications’ title, abstract and journal name was used to determine if the extracted publications were within the field of vehicle electrification. The next and more difficult step was

to determine if all relevant publications were included. This was addressed using publication lists from researchers in the field as well as all publications for the Swedish Electromobility Centre. Further details about the methodology are given in [8].

Preliminary results and the methodology were discussed with researchers and other actors working with vehicle electrification. In total, approximately 40 people were consulted, among them the R&D managers at the three large automakers in Sweden; Volvo Cars, AB Volvo and Scania. Thereafter, modifications were made.

4 Results

4.1 National perspectives

The volumes of vehicle electrification (XEV) publications have increased far more than the overall increase in publications. In Figure 1, the annual production of the16 countries with the highest numbers of XEV publications is shown. In 2011, China overtook the United States in XEV publication volume.

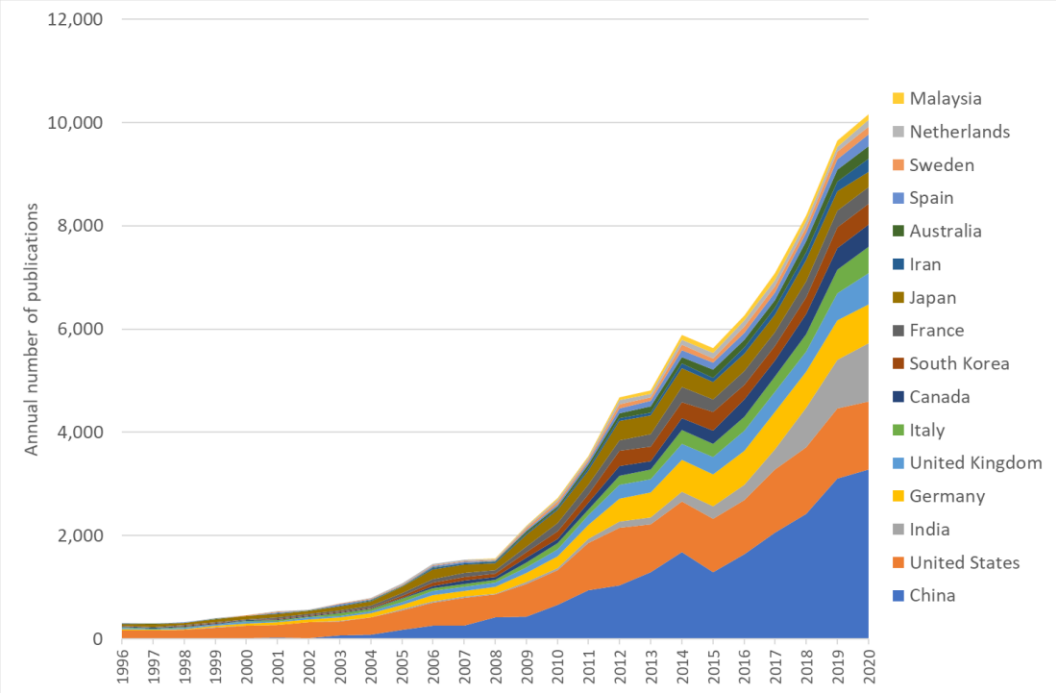

Figure 3: Annual vehicle electrification publication volumes

Table 1 features some indicators characterizing the XEV publications per country. Data for all publications in each country is also given to allow for comparisons. In line with Figure 3, China's publication volume is the largest with more than 12,400 publications over the five-year period 2016 - 2020, which is approximately twice the volume of XEV publications produced in the second largest country, the United States.

Table 1: Key indicators for XEV publications 2016 - 2020

	Publication volume XEV 2016 - 2020	Annual publication volume growth 2016 - 2020 (CAGR)		Citation impact (FWCI)		Share of academic-corporate co-publications		International co-publications (FWIS)	
		XEV	National	XEV	National	XEV	National	XEV	National
Australia	975	12%	3%	2.12	1.60	3.5%	3.2%	1.57	1.38
Canada	1,871	6%	2%	2.00	1.48	6.6%	4.3%	1.40	1.32
China	12,490	16%	9%	1.32	1.06	6.2%	2.7%	0.61	0.55
France	1,478	4%	0%	1.44	1.30	13.3%	6.3%	1.57	1.35
Germany	3,594	3%	1%	1.39	1.35	17.6%	6.5%	0.77	1.20
India	3,530	34%	7%	0.98	0.87	2.3%	1.3%	0.42	0.44
Iran	847	19%	6%	1.95	1.08	0.6%	0.7%	1.06	0.62
Italy	1,884	15%	4%	1.91	1.46	8.8%	4.0%	1.14	1.14
Japan	1,764	-1%	1%	1.07	0.94	12.4%	5.9%	0.64	0.71
Malaysia	571	2%	5%	1.27	1.02	0.5%	1.5%	1.19	1.10
Netherlands	599	0%	2%	1.88	1.75	10.2%	7.3%	1.28	1.51
South Korea	1,705	10%	3%	1.37	1.06	9.6%	4.5%	0.56	0.69
Spain	880	10%	4%	1.55	1.29	9.7%	3.9%	1.34	1.18
Sweden	637	6%	2%	1.97	1.65	17.9%	7.9%	1.27	1.56
United Kingdom	2,289	11%	1%	2.10	1.55	12.8%	5.6%	1.48	1.36
United States	6,253	5%	1%	2.08	1.39	8.0%	4.7%	1.08	0.87
World	44,012	10%	3%	1.36	1.00	6.6%	2.7%	0.54	1.00

In the third and fourth columns, the publication volume growth from 2016 to 2020 was based on a linear regression approximation of the data points for each country and year followed by a calculation of the compounded annual growth rate. India shows a very rapid growth. For most of the countries, XEV publication volumes grow more rapidly than the national average, which is also confirmed on the world level with 10% growth for XEV versus 3% for all publications.

The field-weighted citation impact is a proxy for publication quality. It is a normalised indicator comparing the number of citations that a publication receives with the citation volumes for other publications in the same scientific field, published the same year, in the same type of publication. The global average is 1. Almost all countries have higher FWCI for XEV publications than for average publications. To some extent a high FWCI confirms that the field is "hot" and rapidly growing.

The share of academic-corporate co-publications reflects academic-corporate collaboration. XEV publications involve corporate actors to a higher degree than average publications. In several countries, the shares are very high. This has been investigated more in detail below.

Finally in Table 1, another normalised indicator based on international co-publications with a global average of 1 (see [9]) shows no clear pattern in how international the vehicle electrification research is. A comparison of Germany and France reveals large differences. Whereas Germany has a much lower share of international co-publications in the XEV area than nationally, France has a slightly higher score.

Which countries are in relative terms most active in XEV research? In Table 2, three relative indicators are given comparing the XEV publication volumes with automotive, national and global volumes of publications.

Table 2: XEV publications relative (2016 – 2020)

	XEV share of automotive	XEV share of national	Share of XEV world
Australia	30%	0.18%	2.2%
Canada	41%	0.33%	4.3%
China	43%	0.40%	28.4%
France	32%	0.24%	3.4%
Germany	29%	0.38%	8.2%
India	29%	0.39%	8.0%
Iran	41%	0.28%	1.9%
Italy	32%	0.30%	4.3%
Japan	35%	0.26%	4.0%
Malaysia	22%	0.33%	1.3%
Netherlands	31%	0.19%	1.4%
South Korea	33%	0.39%	3.9%
Spain	29%	0.17%	2.0%
Sweden	25%	0.29%	1.4%
United Kingdom	33%	0.21%	5.2%
United States	30%	0.18%	14.2%

Interestingly, China has the highest shares in all three comparisons. Given the search query for XEV publications, the leading position in the XEV share of all national publications could be interpreted as China having more applied research than the other countries. Some of the traditional countries with a large automotive industry do not appear to have a corresponding volume of research.

As described in the methodology section, a separate analysis of enabling technologies was also made. Given the very wide range of applications for these technologies, the volume of research is not directly linked to the capability to develop more advanced electrified vehicles. However, it is probable that a large share of the researchers in these fields can contribute.

4.1.1 Battery publications

Batteries are needed for all types of electrified vehicles. Many chemistries compete and the processes within the battery cells are difficult to understand. The volumes of scientific publications have increased rapidly during 2016 – 2020 and this is in line with the trend from previous years, see Table 3.

Table 3: Key indicators for battery publications

	Publication volume batteries 2016 - 2020	Publication volume growth 2016 -2020 (CAGR)		Batteries share of automotive	Batteries share of national	Share of batteries world
		Batteries	National			
Australia	2,770	15.0%	2.8%	86%	0.51%	3.3%
Canada	2,191	10.7%	2.1%	48%	0.38%	2.6%
China	40,060	18.1%	9.5%	136%	1.28%	47.4%
France	2,048	6.4%	-0.2%	45%	0.33%	2.4%
Germany	5,104	8.2%	1.0%	41%	0.55%	6.0%
India	4,661	17.3%	7.1%	38%	0.52%	5.5%
Iran	723	22.4%	6.4%	35%	0.24%	0.9%
Italy	1,542	7.3%	4.2%	26%	0.24%	1.8%
Japan	3,867	5.2%	0.8%	76%	0.57%	4.6%
Malaysia	689	9.5%	5.1%	26%	0.39%	0.8%
Netherlands	497	9.4%	1.9%	26%	0.15%	0.6%
South Korea	5,826	7.1%	2.8%	114%	1.32%	6.9%
Spain	1,533	8.3%	3.7%	51%	0.30%	1.8%
Sweden	853	9.8%	1.7%	34%	0.38%	1.0%
United Kingdom	2,852	11.9%	0.8%	41%	0.26%	3.4%
United States	14,266	5.6%	0.5%	69%	0.41%	16.9%
World	84,439	11.8%	3.3%	n/a	n/a	n/a

China dominates with almost 50% of the publications and a rapid growth which indicates that the share will soon be even higher. South Korea and Japan, which historically have been dominating the battery development and production in the world, exhibit rather low shares of battery publications and a less rapid increase than the world average. Still, battery research represents the largest share of all publications in South Korea.

4.1.2 Fuel cell publications

Fuel cells for automotive applications are predominantly of the polymer electrolyte (PEM) type, which means that they operate at relatively low temperatures. The query extracting fuel cell publications included all types. As highlighted in Table 4, fuel cell research is when measured by publication volumes approximately half the size of battery research. Moreover, the volume is increasing at a lower rate than the overall publication volume, which means that the share is decreasing.

Table 4: Key indicators for fuel cell publications

	Publication volume fuel cells 2016 - 2020	Publication volume growth 2016 -2020 (CAGR)		Fuel cells share of automotive	Fuel cells share of national	Share of fuel cells world
		Fuel cells	National			
Australia	1,007	0.1%	2.8%	31%	0.19%	2.2%
Canada	1,569	0.0%	2.1%	34%	0.27%	3.5%
China	14,418	9.2%	9.5%	49%	0.46%	31.9%
France	1,707	-1.3%	-0.2%	37%	0.27%	3.8%
Germany	2,526	-1.1%	1.0%	20%	0.27%	5.6%
India	3,903	7.7%	7.1%	32%	0.43%	8.6%
Iran	1,641	6.8%	6.4%	79%	0.53%	3.6%
Italy	1,570	-1.8%	4.2%	27%	0.25%	3.5%
Japan	2,838	-4.5%	0.8%	56%	0.42%	6.3%
Malaysia	966	4.2%	5.1%	37%	0.55%	2.1%
Netherlands	388	-4.0%	1.9%	20%	0.12%	0.9%
South Korea	2,781	0.6%	2.8%	54%	0.63%	6.1%
Spain	1,105	-4.2%	3.7%	37%	0.22%	2.4%
Sweden	520	1.9%	1.7%	21%	0.23%	1.1%
United Kingdom	2,003	-0.7%	0.8%	29%	0.18%	4.4%
United States	5,691	-1.8%	0.5%	27%	0.16%	12.6%
World	45,221	2.4%	3.3%	n/a	n/a	n/a

China is dominating also in fuel cell research with approximately one third of all publications in the world and the fastest increase over the period 2016 - 2020. India also had a high growth rate and a large share of the world.

4.1.3 Electric machines and power electronics

Finally, the development of research in electric machines and power electronics is probably the most general field, which means that it does not link so strongly to vehicle electrification. The volume of publications is on par with the battery field but the growth rate is clearly lower, see Table 5.

Table 5: Key indicators for electric machines and power electronics publications

	Publication volume electric machines and power electronics	Publication volume growth 2016 -2020 (CAGR)		Machines share of automotive	Machines share of national	Share of machines world
	2016 - 2020	Machines	National			
Australia	1,482	8.0%	2.8%	46%	0.27%	1.7%
Canada	2,387	0.6%	2.1%	52%	0.42%	2.7%
China	22,502	10.4%	9.5%	77%	0.72%	25.2%
France	2,870	-0.3%	-0.2%	63%	0.46%	3.2%
Germany	4,732	1.5%	1.0%	38%	0.51%	5.3%
India	10,718	7.4%	7.1%	87%	1.19%	12.0%
Iran	2,445	9.8%	6.4%	117%	0.80%	2.7%
Italy	3,003	4.2%	4.2%	51%	0.47%	3.4%
Japan	3,710	-2.6%	0.8%	73%	0.55%	4.2%
Malaysia	1,177	-3.7%	5.1%	45%	0.67%	1.3%
Netherlands	553	3.2%	1.9%	29%	0.17%	0.6%
South Korea	3,079	0.6%	2.8%	60%	0.70%	3.4%
Spain	1,925	4.0%	3.7%	64%	0.38%	2.2%
Sweden	678	-3.5%	1.7%	27%	0.30%	0.8%
United Kingdom	3,956	-0.3%	0.8%	57%	0.36%	4.4%
United States	9,276	0.8%	0.5%	45%	0.27%	10.4%
World	89,374	4.4%	3.3%	n/a	n/a	n/a

India is the second largest producer of publications in this field, after China, which makes one quarter of all publications and has the highest growth rate.

4.2 Automaker involvement in research

A less common perspective when looking at scientific publications is how the corporate actors participate. Data for a selection of automakers representing different countries and vehicle types and two Tier 1 suppliers are presented in Table 4. Robert Bosch has the largest total volume of scientific publications, whereas General Motors has the highest number of such publications relating to vehicle electrification, albeit with a negative trend. Toyota had the highest share of electrification publications during the period.

Table 4: Electrification publications with corporate (co-)authors

Scopus publications	All		Electrification		Share
2016 - 2020	Volume	Trend	Volume	Trend	electrification
AB Volvo	510	-2.1%	32	-2.5%	6.3%
BMW Group	1,293	7.5%	125	10.3%	9.7%
Daimler AG	1,174	-0.8%	176	6.1%	15.0%
FAW Group Corporation	553	2.7%	48	11.5%	8.7%
Ford Motor Company	2,094	-2.7%	297	0.8%	14.2%
General Motors	1,799	-4.5%	317	-9.2%	17.6%
Honda Motor Co., Ltd.	868	9.7%	85	0.0%	9.8%
Hyundai Motor Company	720	2.5%	124	-2.2%	17.2%
Scania AB	218	-4.7%	23	11.3%	10.6%
Toyota Motor	1,277	-5.0%	280	-9.7%	21.9%
Volkswagen AG	1,638	3.2%	179	-2.9%	10.9%
Volvo Cars	533	1.1%	42	5.9%	7.9%
DENSO Corporation	646	-9.9%	99	-8.9%	15.3%
Robert Bosch GmbH	2,335	3.3%	268	-4.6%	11.5%

Compared to the analysis in 4.1, this subsection includes all publications where the automotive actor has an affiliation as it is very probable that their research is related to vehicles.

Another perspective on automakers' publications is to what extent they are co-authored with academic actors. The definition of an academic-corporate co-publication is that it has at least two co-authors and at least one academic and one corporate affiliation. This means that also double or multiple affiliations including academic and corporate actors qualify, as long as two authors are involved. In Figure 4, the field-weighted citation impact (FWCI) is indicated for publications with and without such collaboration.

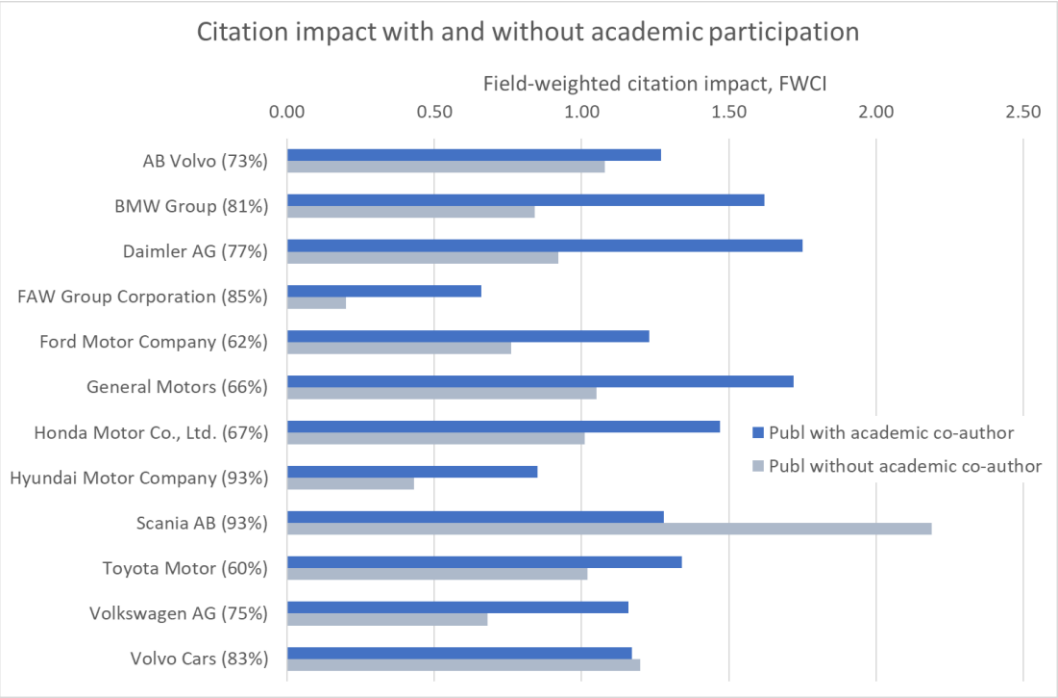

Figure 4: Automaker publications with and without academic actors 2016 - 2020

Directly behind each automaker's name the percentage indicates how large the shares of publications including academic co-authors are. It could be noted that Hyundai and Scania almost exclusively publish with academic participation. The main message in Figure 4 is that collaboration with academic actors leads to a higher citation impact. Scania is an exception, but it should be noted that the number of publications without academic participation is very small (15 publications).

Sweden's FWCI for the period was 1.65 (see Table 1). Publications involving the three Swedish automakers had a clearly lower FWCI. In the discussion with the R&D managers at the automakers, the main hypothesis was that a large share of the publications were made by junior researchers, not least PhD candidates. This could lead to a lower citation impact.

In the highly international automotive industry, it could be expected that also research collaboration is international. The main trend in research is towards more international co-publications and academic-corporate co-publications are no exception, cf. [10]. However, the analysis shows that publications involving the automakers are to a large extent national and the academic partner is often even regional, which means often in the same city as the main research facility. General Motors has more international than national publications, otherwise the share of international co-publications is much lower than for the home country of the automaker.

Another rule of thumb is that international co-publications are more cited than national. In Figure 5, the FWCI for national and international publications are indicated. In this aspect, the automotive industry is in line with the norm, the international co-publications are typically more cited. The numbers at the end of each bar tell the number of publications in the period.

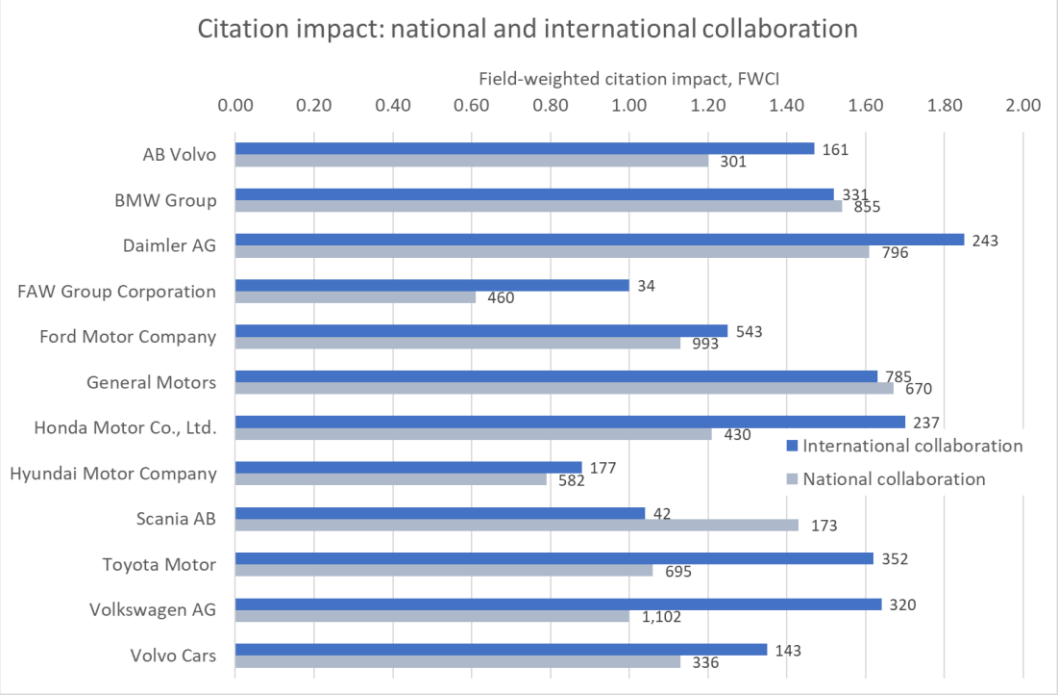

Figure 5: National and international co-publications 2016 - 2020

5 Discussion

Method and data differ from previous studies. The Scopus database is broader and includes more publications in the softer sciences than the web of science, which was used in most other studies. Another advantage of the study is that the development of the search queries is clearly presented, contributing to increased transparency. Even though it is almost impossible to tell how large share of the publications within the enabling technologies that is relevant for vehicle electrification, the inclusion of these technologies and publications allows for a better understanding of how the field is developing. It should also be noted that several indicators such as the citation impact and the share of academic-corporate publications are included, which contribute to perspectives on how various countries approach vehicle electrification. However, the broad scope of the study is also a disadvantage, as many questions remain to be studied more in detail.

What do the results indicate? Even though the approach is somewhat different, the study confirms previous studies' trends towards more publications in China and India, and a lower share in western countries. China is now the largest producer of XEV publications as well as publications in the enabling technologies. It should also be noted that it is not only quantity, publications including Chinese authors are also cited. For example, battery research with Chinese participation had a FWCI meaning that these publications were cited more than twice the global average during 2016 - 2020.

The automotive industry has been and is very international in almost all aspects. It is surprising that the research is not so international. Germany's XEV publications had a FWIS of 0.77, which is lower than the average publication globally (FWIS = 1) and much lower than the German average publication (FWIS = 1.20). Why? Is it because automotive research is more applied than typical research or is it funded differently? This aspect clearly deserves a closer study.

The enabling technologies develop differently. The volume of battery publications increases dramatically whereas the fuel cell publications do not increase at all. Battery publications also have a very high citation impact.

China dominates in all three enabling technologies but especially so in batteries with approximately 50% of the global output.

Whereas battery electric vehicles now have been on the market with growing volumes for a couple of years, fuel cell vehicles are at least one step behind. This could lead to a shift in focus for battery electric vehicles towards more applied questions and thus less research generating publications. Obviously, this is not the case. A better attempt to explain the difference could be that batteries are needed in all types of electrified vehicles and used in many different ways. This, in combination with the still quite high number of competing battery chemistries, and the often very complicated chemical reactions that constitute the function of the batteries, could motivate a continued high volume of research. Fuel cells are less complicated and therefore the focus might be more on engineering issues.

The study of publications including the automakers (and to some extent two Tier 1 suppliers) revealed that a large share of the publications also included academic actors. This was expected. There appear to exist differences between US and Japanese automakers on one hand with relatively lower shares of academic-corporate co-publications and European and South Korean automakers with higher shares. A capacity to make scientific publications in-house could be considered a strength but it could also just signal that the traditions differ between the countries and companies.

As expected, publications including academic actors as well as international co-publications were rewarded with a higher citation impact. The strong preference for national and even local collaborations with academic actors might signal that other aspects than scientific excellence are important when selecting the academic partners. Obviously, one such aspect is the potential for recruitment. It is probably much easier to recruit new employees locally than nationally or internationally.

6 Conclusions

This paper forwards a methodology to study research relating to vehicle electrification using Scopus publications. The results cover 16 countries with the highest number of vehicle electrification publications. Among them, China is by far the largest and the dominance was increasing during 2016 - 2020. This is true for publications directly relating to vehicle electrification as well as for the enabling technologies batteries, fuel cells and electric motors with power electronics. In comparison to average national publications, the vehicle electrification publications are rewarded with higher citation impact and they are also to a higher extent including corporate actors. Among publications including the automotive industry, Robert Bosch has the highest total volume of academic publications, General Motors the highest number of vehicle electrification publications and Toyota the highest share of vehicle electrification publications.

Acknowledgements

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Authors

Hans Pohl (PhD) is Project Manager at Lindholmen Science Park and Program Director at STINT. Pohl's research interests are vehicle electrification, international collaboration and scientometrics. Previous positions include Analyst at Sweden's Innovation Agency, and Area Manager at ABB Switchgear. EVS-13 in Osaka was Pohl's first.

Magnus Karlström (PhD) is Project Manager at Lindholmen Science Park and researcher at Chalmers University of Technology. Karlström's research interests are fuel cell vehicles, electromobility, strategy, life cycle assessment, and business intelligence. EVS-25 in Stavanger was Karlström's first.