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Industrialization of hybrid electric vehicle technology: identifying critical resource dimensions

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Abstract The purpose of this study is to identify critical resource dimensions for the industrialization of hybrid electric vehicle technology. This study focuses on small- and medium-sized technology-based firms in Sweden that employ between 1 and 500 employees and that could be potential suppliers of hybrid electric vehicle technology. The empirical data were collected using a survey (questionnaire) and it covers 40 technology-based firms in eight industrial branches in Sweden. We have included 18 variables in order to identify critical resources regarding Business and R&D networks in three dimensions: ideas and advice, production, and R&D. Two regression models developed for battery systems and battery cells have significant findings. Networks with universities and consultants are especially important. One operative way is building strategic alliances with other firms. The main contributions of this study are empirical support that network resources are necessary and important in battery systems and battery cells and, more broadly, networks are necessary systems for technology shifts in the hybrid electric vehicle industry.

Keywords Hybrid electric vehicle technology · Battery systems · Battery cells · Business and R&D networks · Product innovation · Technology shifts

JEL Classification O14 · O32 · O33

1 Introduction

Swedish vehicle manufacturers are dependent on imports to be able to manufacture hybrid and electric vehicles (HEV). Simultaneously, there are several national suppliers of power electronics for industrial use. Therefore, in order for the power electronics suppliers to approach the vehicle industry, they may need to make adaptations or innovations to their

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products. According to Magnusson and Rickne (2009), being a small country with a limited domestic market, Swedish car production is only marginal from a global perspective. Moreover, in 2007, the production of the Swedish car manufacturers Volvo Cars and Saab Automobile amounted to only 0.6 % of the total production worldwide. However, the Swedish heavy vehicle industry (e.g. trucks, buses, etc.) has a strong position; in 2007, the Swedish heavy vehicle manufacturers Volvo and Scania had as much as 28 % of the European market share and controlled about 10 % of the world's production of heavy commercial vehicles (Magnusson and Rickne 2009). The automotive industry is important for the Swedish economy (Magnusson and Rickne 2009). Automotive exports in 2008 amounted to 13 % of total Swedish exports and the industry's R&D spending is only surpassed by the information and communication technology sector (Norgren et al. 2007). Policymakers are therefore wondering how power electronics and battery suppliers currently access resources, and what resources are important for their further development.

Bai et al. (2012) state that through an understanding of the development of the electric vehicle trends, there is a possibility of the Swedish automotive industry making breakthroughs in the electric vehicle industry such as developing characteristics of the electric car industry layout, the technology roadmap, industrial supporting model, and policy measures, etc. These authors classify and describe the development situation regarding the new energy automobile as: (1) battery electric vehicles, (2) HEV, and (3) fuel cell vehicles. Power electronics have become an integral part of HEV applications (DMC 2010). Thus, with the advent of technologies, automotive users started using power electronics in HEV applications. The 'Power Electronics in Electric and Hybrid Vehicles Report' (Roussel 2009) details power electronic applications in the HEV and electric vehicle markets, and includes technologies and market trends. According to the report, power electronics modules today represent 20 % of the material costs for HEV. Further, strong growth in this sector is expected: over 30 % between 2009 and 2020 (Roussel 2009). One of the major validation and safety challenges to be tackled in modern HEVs concerns the effective testing of the battery pack itself. The battery management systems (BMS), the complex electronic system that manages the performance and safety of the battery pack, and the high levels of electrical energy stored within (DMC 2010). Collection of data from the pack sensors and activation of the pack relays are accomplished by the pack's battery monitoring unit (BMU).

The economic benefits of electric drive vehicles discussed in Link et al. (2015) include the reduced fuel consumption in heavy-duty diesel trucks, the application of laser and optical diagnostics, and combustion modelling. The health and environmental benefits considered in their study resulted from reduced diesel fuel consumption, which leads to reduced emissions, which in turn leads to reduced greenhouse gas and air pollutants. Link et al. (2015) also state that sales of hybrid electric vehicles using Li-ion battery technology began to grow in 2012. Moreover, with a market growth and arrival of firms at the different levels (e.g. car makers, battery suppliers, semiconductor-firms, etc.), the landscape will change drastically. Automotive producers are investing heavily in hybrid electric vehicles, and will play an important role in the value chain of hybrid electric vehicle power devices. These firms have the knowledge of specific automotive requirements for power devices. Hence, it will be difficult over the next few years for power modules manufacturers to find a significant place in the hybrid electric market.

The purpose of this study is to identify critical resource dimensions for industrialization of hybrid electric vehicle technology. We have included 22 variables in this study regarding different levels and resource dimensions to identify critical resources for business and R&D networks, including ideas and advice, production, and R&D. Four central products of hybrid vehicle technology are investigated—battery systems, BMS/software, BMU, and battery cells. The paper is exploratory to its nature and the arguments presented in this paper recognize the complex nature of co-operative resources. This study is a descriptive technology study, which should be of interest to scholars, practitioners and policymakers regarding innovation, technology management, and technology transfer activities.

This study focuses on small- and medium-sized Swedish technology-based firms that employ between 1 and 500 employees and that has a supplier perspective. The empirical data contains a survey of Swedish 40 firms in eight industrial branches that could be potential suppliers of hybrid vehicle technology. In Sect. 2, there will be a brief review of the literature and we present the research question of the study. Section 3 describes and justifies the sample, data collection process, and the measures of investigation, while in Sect. 4, we account for the analytical processes applied and the results. Finally, in Sect. 5, we present our conclusions and future research directions.

2 Literature and research question

2.1 Technological change and shifts

Major technological innovations represent technical advances so significant that no increase in scale, efficiency, or design can make older technologies competitive with the new technology (Mensch 1979; Sahal 1981). These major technological shifts can be classified as competence-destroying or competence-enhancing because they either destroy or enhance the competence of already existing firms in an industry (see also Abernathy and Clark 1985). The former require new skills, abilities, and knowledge in both the development and production of the product. Henderson (1988) discusses the relationships between components, system parameters, and user needs. Here, performance means, 'the set of customer demands that a physical performance enables (the product) to meet is the set of user needs that is satisfied' (Henderson 1988, p. 30).

Henderson underlines that 'generational innovation' requires a new understanding of these relationships, while radical innovation destroys most of an existing framework by fundamentally changing the components. Henderson and Clark (1990) also further developed the systematisation between different categories of innovations by combining changes in the two types of knowledge. They define component knowledge as 'the knowledge about each of the core design concepts and the way in which they are implemented in a particular component' and architectural knowledge as 'knowledge about the ways in which the components are linked together into a coherent whole' (Henderson and Clark, p. 11). They also claim that depending on what type of knowledge it is that changes, or depending on whether it is components or links between components that change, innovations are said to be incremental, modular, architectural, or radical.

Radical innovation, such as patents, is more uncertain and more complex than incremental innovation, and its management requires a different set of practices (Leifer et al. 2000; Slater et al. 2014). Several studies, such as Crossan and Apaydin (2010) and Slater et al. (2014), have called for studies into radical innovation management in order to show whether or not it is similar to incremental innovation management. Radical innovation is based on a set of scientific and engineering principles that opens new markets and potential applications (Ettlie et al. 1984; Chandy and Tellis 1998; Dewar and Dutton 1986; McDermott and O'Connor 2002; Menguc et al. 2014).

Pohl and Elmquist (2010) compared Volvo Cars and Toyota's successful but resource-demanding Prius project, and their study reveals some factors contributing towards rapid development in a context of limited resources, including (1) focused project objectives, (2) tight collaboration with suppliers of the new technologies, (3) reuse of existing technologies and (4) an unaggressive, bottom-up approach in order to change the firm's values, norms, and other core capability dimensions. The authors provide an empirical illustration of how a small firm in a mature industry worked with radical innovation in a development project drawing on the combination of organizational slack, entrepreneurial employees, and an extensive use of external knowledge suppliers.

According to Pohl (2010), technological change can be divided into two categories: in line with the mainstream trajectory or paradigm (continuous, incremental), or breaking with the mainstream (discontinuous, radical). Pohl's doctoral thesis aims to increase the understanding of the latter type: paradigmatic shifts in technology. These shifts are meandering processes lasting years or even decades, and pose a serious threat as well as an opportunity to the actors involved. The empirical case of Pohl's thesis is the automotive industry and its potential shift from the internal combustion engine to electric propulsion. His thesis discusses a new theoretical concept of 'interparadigmatic hybrids', whilst aiming to enhance understanding of the process that constitutes a paradigmatic shift in technology. It is argued, using this concept, that policy has targeted full electrification that is incorporated into vehicles with fuel cells or large batteries. According to Pohl (2010), the gradual shifts in various hybrid electric vehicle solutions have been largely ignored.

2.2 Business and R&D networks

The notions that networks are important in product innovation and production and that firms will build networks if they are close seems to satisfy some need for arguments. The business and R&D network can be seen as a resource in itself when the firm acquires access for resources and capabilities through the network such as capital innovation and advice (Zukin and DiMaggio 1990; Uzzi 1996, 1997; Gulati et al. 2000). Entrepreneurial networks can be categorized into formal and informal networks (Birley 1985). Informal networks are recognized as including personal or friendship relations, family ties and business partners. Formal networks consist of suppliers of capital such as venture capitalists, banks, creditors, and professionals such as accountants, lawyers, and trade associations (Das and Teng 1997).

According to Aaboen et al. (2008), economic theory lays down the efficiency conditions governing the allocation of existing resources (i.e. resources being used in current production) and future resources. Innovative resources are required to produce technological innovation. Christensen (1996) has proposed a framework that distinguishes several generic categories of innovative assets, including: (1) scientific research assets, which provides direct inputs into process development and new product application, involve both (2) basic research of a pre-competitive nature and (3) applied and/or industrial research; (4) process innovative assets; (5) product innovative application assets (technical application and functional application); and (6) aesthetic assets. Successful commercial exploitation of technological innovation mainly requires access to assets that are complementary to innovative assets (Teece 1986).

The network grouping can be seen as an alliance where a trading of knowledge between the alliances takes place (Anand and Khanna 2000). This alliance holds an idiosyncratic aspect that develops a 'common good.' The network is created through a path dependent process, and is therefore, idiosyncratic and difficult to imitate being a subject of immobility, imitability, and non-substitutional (Grant 1991; Gulati 1999). Other barriers to mobility exist where resources are firm specific, and where property rights are called co-specialized (Peteraf 1993). There are barriers that hinder the duplication of resources such as uncertain inimitability (Lippman and Rumelt 1982), complexity, tacitness and specificity (Reed and DeFillippi 1990), economics of scale, producer learning and information impactedness (Rumelt 1984, 1987).

Proximity is identified as a condition for developing a network structure (Powell et al. 1996; Soh 2003; Walker et al. 1997). Santoro and Gopalakrishnan (2001) showed that trust, geographic proximity and flexible university policies for intellectual property rights, patents, and licences were strongly associated with greater technology transfer activities. Jones-Evans (1996) argues that firms with a competence structure primarily based on technology had a tendency to underperform in comparison with firms with both business and technology knowledge. This shortage of knowledge is then a barrier for developing the technological competence into an innovation (Freel 2000). The proximity between technology firms and the university promotes an exchange of ideas (Deeds et al. 2000) and, as Balconi et al. (2004) argue, it is the geographical realm that supports the wider structure of university plus industry for networking and technology transfer (for studies on technology transfer, see for example Niosi 2006a, b). In addition, the proximity to important customers, competitors, incubator status, and facility cost could be important factors regarding localization.

Research suggests that firms in dynamic environments with higher levels of information processing, communication, and knowledge transfer are more likely to develop competencies that will result in successful technology innovation than firms in these environments with lower levels of co-operative resources (Henderson and Cockburn 1994). Westhead (1997) says that there is a growing literature surrounding the relationship between a firm's environment and its ability to innovate (Davelaar and Nijkamp 1989; Kleinknecht and Poot 1992; Feldman 1994; Goss and Vozikis 1994; Pfirrmann 1994, 1995; Leung and Wu 1995).

In summary, innovative resources must comprise a fit between the technology dimension and the management dimension; that is, the technology-based firm must focus on how to obtain access to complementary business resources to technological innovation. Our study will analyse business and R&D networks in three dimensions: ideas and advice, production, and R&D.

Our research question is:

RQ *How are the firm's business and R&D networks, including ideas and advice, production, and R&D, related to industrialization of hybrid electric vehicle technology?*

Our study will consequently focus on the subset of network resources of a firm identified as business and R&D networks and industrialization defined as production of hybrid electric vehicles. However, successful commercialization may depend on other organizational resources in the firm to support and complement new products emanating from R&D.

3 Methods

3.1 Sample

This study focuses on small- and medium-sized (SME) technology-based firms in Sweden that employ between 1 and 500 individuals and are as potential suppliers in the hybrid electric vehicle industry. SMEs represent 99 % of all firms in the EU. They provide around 65 million jobs and contribute to entrepreneurship and innovation (European Commission 2013). Therefore, in order to identify the SME-population, we used two main sources: the SCB and Lindberg and Eriksson (2010).

1. From SCB (Statistics Sweden, 2011), we could identify 116 SME firms employing between 1 and 500 individuals with activity in one of the following three different sectors: batteries and accumulators, power electronics and electric machines, and generators and transformators (SNI codes 27200, 29310 and 27110, respectively). All 116 firms registered in the appropriate industry classification codes were retrieved from Statistics Sweden. SNI codes 10–33 are production, and of the 116 SMEs from the SCB, we were able to use 69 firms. The rest of the firms were disregarded because they did not fit the selection criteria of suitable products of potential suppliers to hybrid vehicles (control parameter).
2. Lindberg and Eriksson (2010) identified 59 potential Swedish electromobility suppliers. Therefore, in this study we will analyse 41 firms of these 59 firms (SNI codes: 261, 271, 272, 291, 293, 302, 304, 309, and 721) from Lindeberg and Eriksson's report.

Thus in the second phase, we used the report from Lindberg and Eriksson (2010) to identify relevant firms. We removed 65 firms after further studies and checking the firm's businesses with Bolagsinfo, a database at Chalmers University Library (lib.chalmers.se). The eight branches represented among the remaining firms are: transportation industry, electronic industry—general, electronic industry—vehicles, machines/plastics/batteries, data/IT/telecommunications, technology consultants, R&D (biotechnology), and wholesale trade (e.g. vehicles, electronic equipment, etc.). The firms were private joint-stock firms. After removing duplicate entries and confirming from the initially identified 175 firms, we identified a total of 110 relevant firms.

Thus, in the third phase, we identified six different manager positions in the firms that could be suitable respondents to the survey: R&D manager, technical manager, development manager, production manager, construction manager, and managing director. Moreover, we contacted the Swedish Posten, the Nordic region's largest messaging and logistics operator, to get the names, addresses, and email-addresses of the positions. Firms without one of these four positions were removed from the sample (control parameter). The survey was sent out in autumn 2011 and the response rate was 47.1 %. A quantitative approach is used in order to identify resource dependencies among all the suppliers of power electronics in Sweden. The survey included questions about what resources they need, and the importance of different relationships in relation to different resources.

3.2 Data collection

After initial tests at a vehicle producer (AB Volvo), questionnaires were administered in the end of October 2011 to the sample, the 110 SME technology-based firms in Sweden. Written questionnaires were administered by regular post to identified respondents in the following priority: technical manager, development manager, production manager, and managing director. We sent the questionnaire to one person at each firm. Additional, 25 firms were rejected from the sample at this point because they fell outside the sample frame, which in most cases, meant that firms were in the wrong branch with wrong products. The total number of firms included in the sample was thus reduced to 85. After four reminders by email, we received valid responses from 40 firms. This represents a response rate of 47.1 %, a figure that compares favourably with mail surveys of SME firms. A no response analysis was done regarding sales, total assets, profit margin, employment, age, and branches.

Therefore, of the 40 firms that have responded to the survey, 21 firms are from the SCB list of firms, and 19 firms are from the report from Lindberg and Eriksson (2010). However, our intention was that all firms should be SME, but we have included three firms that have more than 500 employees from the database in Lindberg and Eriksson's report. We have decided to include these three firms with more than 500 employees because these three firms are important regarding suppliers in the hybrid vehicle industry in Sweden. The data from these three questionnaires are included in our database, but we have removed the firm's business data from the table below, because they are regarded as outliers. We have three more firms with more than 500 employees (also from Lindberg and Eriksson's report) that have not responded to our survey, so we removed their business data from the table below (No response). We have also removed outliers in Table 1 regarding extremely high negative profit margins (>-100 %).

In its introduction, the questionnaire clearly stated that it was purposefully addressed to suppliers or potential suppliers in production of hybrid vehicles in Sweden. Additionally, several of the sections contained questions concerning products, innovation performance, resources, networks and cooperation, localization, planning and the environment, and strategic or organizational perspectives. It is our firm belief that the respondents were aware that the questions were to be interpreted in the context of hybrid electric vehicles. Most items were measured on Likert-type scales. Secondary data, data on firms' business performance from 2010, were gathered from a database (Bolagsinfo) at Chalmers University Library (lib.chalmers.se).

Table 1 presents the broad characteristics of the firms involved. Compared to the responding firms, those that had not responded to our survey have higher sales, profit margins, employment, and have larger total assets. Apart from this, the table reveals no significant differences between responding firms and non-responding firms.

Cook and Campbell (1979) define validity as the best available approximation to the truth or falsity of a given inference, proposition, or conclusion. Generally speaking, questionnaires tend to be strong on reliability but the artificiality of the survey format reduces validity. Since managers' perceptions are difficult to capture in terms of dichotomies such as 'agree/disagree' or 'support/oppose', or on Likert scales, as the measures are only approximate indicators. Regardless of the sample size of the study, and the correlations between items in the scale, the reliability of Likert scales drops if the number of options is reduced.

3.3 Measures for investigation

The focus of this study is to understand through the links and the interplay of R&D network dimensions regarding ideas and advice, production and R&D, and how the different power electronics suppliers currently use resources in their business. All measures used in this study (18 variables) consisted of Likert-type scales, from 1 (very little) to 5 (very much), or dichotomies using 1 (Yes) and 0 (No). Table 6 summarizes measures applied in the study. Since all measures are expressed in Likert-type scales or dichotomies, there is no risk of aggregated means being affected by extreme values. Table 5 in the

Table 1 Means and frequencies of surveyed small and medium-sized technology organizations over the 2011 period

1. Sample and response rates: number of employees: 1–500

Firms

N (population): 110	No valid firms[a]: 25
n (response): 40	Response rate (%): 47.1
No response: 45	

2. Business data

	Sample			
	Response		No response	
	Mean	SD	Mean	SD
Sales[b]	51,609	83,524	164,600	278,300
Total assets[b]	152,540	511,598	83,302	166,566
Profit margin[c]	0.41	13.42	5.84	7.09
Employment[d]	39.46	75.40	67.12	104.65
Age[e]	18.08	12.14	20.25	9.78

3. Firm characteristics—innovation performance (response)

	Mean	SD	Scale
Development of patents—product innovation	0.45	0.50	Yes/no[f]
Change of products last 12 months—product innovation	0.69	0.47	Yes/no[f]
Change of products last 12 months—product innovation	3.28	1.06	1–5

4. Branch—frequencies (%)	Sample	
	Response	No response
1. Transportation industry	0.200	0.177
2. Electronic industry—general	0.325	0.400
3. Electronic industry—vehicles	0.025	0.022
4. Machines/plastics/batteries	0.075	0.066
5. Data/IT/telecommunications	0.100	0.044
6. Technology consultants	0.025	0.066
7. R&D—biotechnology	0.100	0.022
8. Wholesale trade (vehicles, elec. equipm. etc.)	0.150	0.200

[a] Control parameters

[b] 1000 SEK

[c] Percent

[d] Number of employees

[e] Years

[f] 1/0

"Appendix" shows the nature and extent of the variable level of business and R&D linkages that exist when correlated with the production of hybrid product systems. The variables are (Table 2):

- Business and R&D networks: A network can be seen as a resource in itself, and through the network the firm acquires access for resources and capabilities such as advice and innovation: all 18 measures were five-point Likert-type scales;
- Battery systems and BMS/software (large systems);
- BMU and battery cells (support systems).

The statistical analysis was conducted in four steps. First, in the correlation matrix in "Appendix" (Table 5) correlations were identified on the variable level between the hybrid electric vehicle technology on the large and support system levels and Business and R&D networks. The correlations are on the 0.05- and 0.01-levels. Second, a factor analysis (principal component analysis) was applied to test whether the measures selected for each construct exhibited sufficient convergence and discriminating validity. Third, a correlation analysis was applied to identify any latent variables that are statistically significant. Fourth, logistic regression analysis was applied to test the link between the independent latent variables and dependent variables.

Table 2 Variables in the study

Variables	Mean	SD	Scale
Business and R&D networks			
1. Suppliers—ideas and advice	3.55	1.55	1–5
2. Customers—ideas and advice	4.15	0.74	1–5
3. Competitors—ideas and advice	1.70	1.11	1–5
4. Universities—ideas and advice	2.35	1.84	1–5
5. Consultants—ideas and advice	2.38	1.56	1–5
6. Patent bureaus—ideas and advice	2.08	1.54	1–5
7. Families—ideas and advice	1.50	1.24	1–5
8. Business organisations—ideas and advice	1.88	1.32	1–5
9. Suppliers—production	3.58	1.57	1–5
10. Customers—production	3.17	1.57	1–5
11. Competitors—production	1.38	1.08	1–5
12. Universities—production	1.48	1.26	1–5
13. Consultants—production	2.10	1.50	1–5
14. Suppliers—R&D	3.35	1.81	1–5
15. Customers—R&D	3.85	1.21	1–5
16. Competitors—R&D	1.23	1.00	1–5
17. Universities—R&D	2.13	1.59	1–5
18. Consultants—R&D	2.32	1.58	1–5
Hybrid electric vehicle technology—production			
19. Battery systems	0.25	0.44	Yes/no[a]
20. BMS/software	0.15	0.36	Yes/no[a]
Hybrid electric vehicle technology—production			
21. BMU	0.10	0.30	Yes/no[a]
22. Battery cells	0.13	0.33	Yes/no[a]

[a] 1/0

4 Analysis

4.1 Factor and correlation analyses

This section reports the responses of firms to questions about the types of research and business networks which are committed by the firms related to different actors, such as business advice, universities and information about the factors which may explain the resources needed to produce hybrid electric vehicle technology. The next step is principal component analysis. However, there are only 40 observations in this study, and what constitutes an adequate sample is somewhat complicated. For example, Preacher and MacCallum (2002) obtained good results with extremely small sample sizes ($p > n$), but Mundfrom et al. (2005) found some cases where a sample size of $n > 100p$ was necessary. They also found that if the number of underlying factors stays the same, more variables (and not fewer, as implied by guidelines based on the observations-to-variables ratio) could lead to better results with small samples of observations. If the conditions are auspicious, a lot fewer observations can be accepted than old guidelines would suggest. Until recently, analysts used rules of thumb like 'factor analysis requires 5–10 times as many subjects as variables.' Recent studies suggest that the required sample size depends on the number of factors, the number of variables associated with each factor, and how well the set of factors explains the variance in the variables (Bandalos and Boehm-Kaufman 2009). In our case, we have also made initial correlations on the variable level to be safe regarding the statistical relationships.

Principal component analysis reveals the presence of four strong latent variables (see Table 3) related to Business and R&D networks in the three dimensions: Ideas and advice, production, and R&D. Four strong latent variables are developed for Business and R&D networks: Universities and consultants ($\alpha = 0.922$), Competitors ($\alpha = 0.843$), Suppliers ($\alpha = 0.875$) and Customers ($\alpha = 0.756$). No variables were dropped from further analysis depending on lack of data reliability. All factor loadings were >0.300 for the 18 variables and Kaiser–Meyer–Olkin (KMO) is 0.805 (minimum of 0.600) and Bartlett's test of sphericity is 0.000. Table 6 in "Appendix" shows the correlations between these four latent variables and the four variables battery systems (large systems), BMS/software (large systems), BMU (support systems), and battery cells (support systems), where the latent variable Universities and consultants seems to be important.

4.2 Regression analyses

The next step is to test for the relationship between the four independent latent variables and the dependent variables: battery systems, BMS/software, BMU, and battery cells. Thus, the four tested logistic regression models are expressed as:

$$BS = \beta_0 + \beta_1 NW1 + \beta_2 NW2 + \beta_3 NW3 + \beta_4 NW4$$
$$BMS = \beta_0 + \beta_1 NW1 + \beta_2 NW2 + \beta_3 NW3 + \beta_4 NW4$$
$$BMU = \beta_0 + \beta_1 NW1 + \beta_2 NW2 + \beta_3 NW3 + \beta_4 NW4$$
$$BC = \beta_0 + \beta_1 NW1 + \beta_2 NW2 + \beta_3 NW3 + \beta_4 NW4$$

where: *BS*, battery systems; *BMS*, BMS/software; *BMU*, BMU; *BC*, battery cells; *NW*1, University and consultants; *NW*2, Competitors; *NW*3, Suppliers; *NW*4, Customers

However, two of the logistic regression models were not significant (BMS/software: sig = 0.245 and BMU: sig = 0.08). Table 2 shows the two significant logistic regression models with the depending variables battery systems and battery cells. The two logistic regression models are significant on the 0.05-level. No individual latent variables are significant and only one latent variable (Competitors) has a negative impact on battery systems (Table 4).

Only firms with internal resources can absorb knowledge and technologies that are co-operatively developed with universities and regarding the research question in this study. Concerning Business and R&D networks, we have developed two significant regression models using battery systems and battery cells with Business and R&D networks. We can also state that BMS/software (large systems) and BMU (support systems) to some are to some extent affected by Business and R&D networks, but only by some of the network variables.

4.3 Discussion

A number of researchers have examined the role of the type of technology in the ability of incumbent firms to adapt innovation opportunities (Abernathy and Utterback 1978; Tushman and Anderson 1986; Anderson and Tushman 1991; Henderson and Clark 1990; Christensen 1997). Some scholars have argued that the organizational strategy of the firm must be aligned with the type of technology they choose to develop (Chesbrough and

Table 3 Oblique rotation of component analysis factor matrix—pattern matrix

Variables Factor name Cronbach α	Factor 1 Universities and consultants α = 0.922	Factor 2 Competitors α = 0.843	Factor 3 Suppliers α = 0.875	Factor 4 Customers α = 0.756
1.	0.231	0.324	0.582	0.096
2.	0.001	−0.174	0.281	0.741
3.	−0.138	0.908	0.060	0.032
4.	0.838	0.112	−0.069	0.032
5.	0.823	−0.130	0.239	0.034
6.	0.461	−0.266	0.585	−0.081
7.	−0.071	0.601	0.314	−0.239
8.	0.219	0.310	0.468	−0.181
9.	0.172	0.205	0.668	0.147
10.	0.267	0.144	−0.357	0.832
11.	−0.141	0.892	0.065	0.218
12.	0.692	0.516	−0.313	−0.164
13.	0.795	−0.144	0.109	0.177
14.	0.005	0.160	0.841	0.093
15.	−0.116	0.024	0.248	0.807
16.	−0.013	0.868	0.142	0.064
17.	0.832	−0.075	0.154	−0.009
18.	0.839	−0.115	0.210	−0.027

Business and R&D networks

Cumulative variance 76.068 per cent

α (Cronbach α) >0.600

KMO = 0.805 and Bartlett's test of sphericity = 0.000

Teece 1996; Tushman and O'Reilly 1997). Technology provides and requires dynamic approaches to managing R&D and knowledge. If firms face a similar external environment, the resource-based theory suggests that those firms with a similar initial resource endowment should display similar patterns of firm behaviour and firm performance. Therefore, in the product innovation area, the process for acquiring new knowledge is especially important (Arora and Gambardella 1994; Davila 2000; Holt 1978).

One important conclusion from our empirical studies is that battery systems and battery cells require Business and R&D network resources for industrialization of hybrid electric vehicle technology, especially networks with universities and consultants. However, the SME firms surveyed in Sweden probably do not have the technological and business knowledge for producing these arduous systems independently. Our empirical studies also raise the question as to whether hybrid strategies and production systems in their present format can support the vehicle manufacturers in Sweden. Therefore, the firms must develop resources and capabilities in order to be quicker in getting involved in the growing hybrid electric vehicle industry. According to Elmuti and Kathawia (2001), not all firms can provide the technology that they need to effectively compete in their markets on their own. Therefore, they are teaming up with other firms who do have the resources to provide the technology and coordinate their resources so that together they can provide the needed technology.

The resource-based theory, for example, has a strong focus on performance, and the theory explicitly recognizes the importance of intangible and tangible concepts. The main contribution of this study is the idea supporting the importance of the need for the resource dimensions for battery systems and battery cells, but also BMS/software and BMU, regarding the hybrid electric vehicle technology. In this study, how the knowledge is structured and processed in the firm is considered as a strategically important resource for these firms. The empirical analysis shows that there are relationships between Universities—Ideas and advice, Universities—R&D and battery systems, BMS/software, BMU, and battery cells. This paper builds on empirical evidence and argues that technology-based firms working with universities may achieve certain advantages regarding the development of battery systems, BMS/software, BMU, and battery cells. In the literature section, it is also argued that proximity is one condition for developing a network structure (Powell et al. 1996; Soh 2003; Walker et al. 1997). Santoro and Gopalakrishnan (2001)

Table 4 Logistic regression models

	Model 1[a]				Model 2[b]			
	B	SE	Wald	Sig.	B	SE	Wald	Sig.
*NW*1	0.091	1.126	0.526	0.468	0.285	1.161	3.157	0.076
*NW*2	−0.200	0.223	0.800	0.371	0.007	0.216	0.001	0.973
*NW*3	0.112	0.176	0.408	0.523	0.012	0.277	0.002	0.967
*NW*4	0.387	0.348	1.238	0.266	0.144	0.420	0.118	0.732
Constant	−8.893	4.560	3.804	0.051	−8.965	5.117	3.070	0.080

* $p < 0.05$

** $p < 0.01$

*** $p < 0.005$

[a] Dependent variable: battery systems—large systems (yes/no: 1/0). Model summary: Cox & Snell R square = 0.229. Nagelkerke R square = 0.427, Model Chi square: 10.121, the model: Sig. = 0.038*

[b] Dependent variable: battery cells—support systems (Yes/No: 1/0). Model summary: Cox & Snell R square = 0.228. Nagelkerke R square = 0.426, Model Chi square: 10.088, the model: Sig. = 0.039*

showed that trust, geographic proximity, and flexible university policies for intellectual property rights have strong relationships with greater technology transfer activities. However, product innovative application assets are the resources and capabilities required to produce product innovation.

One way to solve this situation is building strategic partnerships with other firms, and regardless of the industry or type of business, strategic alliances are a way for a firm to compete and succeed in today's networked economy. There are a number of different ways in which ties can be established between firms in the network (Kim et al. 2011). For instance, a tie or an alliance might be established between two firms if they were collaborating on a new product development, if they had overlapping board membership, or belonged to the same trade organization. Firms can be linked because of the delivery and receipt of materials, or they can be linked through a contractual relationship (Choi and Hong 2002). Furthermore, in a tree-like structure of materials flow, the network describes which firm deliver to which customer (Berry et al. 1994; Chopra and Sodhi 2004). Networks based on contractual relationships can have flows of both materials and knowledge, and it is becoming increasingly important to evaluate not only how firms transact with a given buyer, but also how they interact between themselves to promote knowledge exchange (Stuart et al. 1998, Dyer and Nobeoka 2000).

A limitation in this study is related to the problems encountered when researching knowledge and business resources. The data were based on a single point in time, from single respondents in different firms. Knowledge and business resources evolve over time during a process of interaction and are affected by environmental turbulence. We were not able to capture the evolving nature of this matter in our study. However, it is our belief that we have set out the direction for firms who want to be able to manage the development of battery systems, BMS/software systems, BMU, and battery cells.

5 Conclusions

This study is descriptive in nature and should be of interest to scholars, practitioners, and policymakers in technology and innovation management and especially the area of technology transfer. Our empirical analysis shows that battery systems, BMSs/software, BMUs, and battery cells require Business and R&D resources for the industrialization of HEV technology, and networks with universities are particularly important. It may also be important to build strategic alliances with other firms, and strategic alliances are a way for a firm to compete. Not all SME firms can provide the technology that they need to effectively compete in their markets on their own, and therefore, they are teaming up with other firms who do have the resources to provide the technology or who can pool their resources so that together they can provide the new technology. Future research could explore the multidimensionality of business and R&D networks. In particular, we would encourage qualitative studies to allow for a better understanding of the interplay between the resources and hybrid technology over time.

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Appendix

See Tables 5 and 6.

Table 5 Correlation matrix: business and R&D networks—large and support systems—variable level

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Suppliers—ideas and advice										
2. Customers—ideas and advice	0.402*									
3. Competitors—ideas and advice	0.459**	0.022								
4. Universities—ideas and advice	0.617**	0.263	0.231							
5. Consultants—ideas and advice	0.611**	0.433**	0.135	0.658**						
6. Patent bureaus—ideas and advice	0.465**	0.405*	−0.071	0.478**	0.722**					
7. Families—ideas and advice	0.397*	−0.070	0.442**	0.263	0.115	0.176				
8. Business organ—ideas and advice	0.514**	0.176	0.297	0.294	0.505**	0.399**	0.377**			
9. Suppliers—production	0.785**	0.503**	0.394*	0.519**	0.645**	0.585**	0.255	0.352*		
10. Customers—production	0.344*	0.478**	0.274	0.355*	0.359*	0.120	0.127	0.183	0.262	
11. Competitors—production	0.449**	0.172	0.757**	0.244	0.147	−0.007	0.389*	0.353*	0.413**	0.343**
12. Universities—production	0.338*	−0.012	0.509**	0.622**	0.439**	0.174	0.259	0.262	0.381*	0.177
13. Consultants—production	0.618**	0.438**	0.137	0.626**	0.839**	0.523**	−0.006	0.399*	0.607**	0.441**
14. Suppliers—R&D	0.800**	0.449**	0.311	0.422**	0.552**	0.538	0.176	0.428**	0.883**	0.149
15. Customers—R&D	0.421**	0.650**	0.131	0.299	0.339*	0.360*	0.094	0.216	0.465**	0.606**
16. Competitors—R&D	0.441**	0.030	0.704**	0.308	0.222	0.085	0.448*	0.466**	0.343*	0.170
17. Universities—R&D	0.630**	0.365*	0.030	0.816**	0.756**	0.598**	0.224	0.427**	0.557**	0.290
18. Consultants—R&D	0.606**	0.323*	0.124	0.591**	0.928**	0.677**	0.140	0.536**	0.589**	0.392**
19. Battery systems—large systems	0.299	0.071	0.056	0.357*	0.294	0.162	−0.068	−0.004	0.308	0.093
20. BMS/software—large systems	0.325*	0.357*	−0.164	0.428**	0.347*	0.325*	−0.027	0.088	0.254	0.201
21. BMU—support systems	0.282	0.215	−0.176	0.405*	0.237	0.295	−0.114	0.022	0.265	0.213
22. Battery cells—support systems	0.176	0.250	−0.164	0.334*	0.446**	0.425**	−0.027	0.088	0.254	0.250

	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.	21.
1. Suppliers—ideas and advice											
2. Customers—ideas and advice											

Table 5 continued

	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.	21.
3. Competitors—ideas and advice											
4. Universities—ideas and advice											
5. Consultants—ideas and advice											
6. Patent bureaus—ideas and advice											
7. Families—ideas and advice											
8. Business organ—ideas and advice											
9. Suppliers—production											
10. Customers—production											
11. Competitors—production											
12. Universities—production	0.516**										
13. Consultants—production	0.148	0.405*									
14. Suppliers—R&D	0.362**	0.199	0.472**								
15. Customers—R&D	0.270	0.007	0.330*	0.472**							
16. Competitors—R&D	0.807**	0.523**	0.153	0.3357	0.163						
17. Universities—R&D	0.179	0.453**	0.712**	0.496*	0.341*	0.254					
18. Consultants—R&D	0.157	0.397*	0.835**	0.514**	0.250	0.212	0.754**				
19. Battery systems—large systems	0.157	0.126	0.362*	0.379*	0.082	0.178	0.371*	0.271			
20. BMS/software—large systems	−0.128	−0.209	0.328*	0.255	0.314	−0.089	0.546**	0.309	0.336*		
21. BMU—support systems	−0.096	−0.265	0.298	0.299	0.285	−0.067	0.399*	0.244	0.527**	0.753**	
22. Battery cells—support systems	0.015	0.095	0.431**	0.159	0.122	0.065	0.449**	0.406*	0.518**	0.312	0.465**

** Correlation is significant (0.01-level), 2-tailed, * correlation is significant (0.05-level), 2-tailed

Table 6 Correlation matrix: latent variables and large and support systems

	1.	2.	3.	4.	5.	6.	7.
1. University and consultants							
2. Competitors	0.296*						
3. Suppliers	0.736**	0.440**					
4. Customers	0.426**	0.232	0.446**				
5. Battery systems—large systems	0.355*	0.089	0.290	0.099			
6. BMS/software—large systems	0.363*	−0.120	0.310	0.318*	0.335*		
7. BMU—support systems	0.279*	−0.138	0.293	0.278	0.527**	0.753**	
8. Battery cells—support systems	0.433**	−0.036	0.273	0.241	0.518**	0.312	0.465**

** Correlation is significant (0.01-level), 2-tailed, * correlation is significant (0.05-level), 2-tailed

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