SUPPLEMENTARY MATERIAL

APPENDICES B to I

Internal or external spillovers – which kind of knowledge is more likely to flow within or across technologies

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Appendix B Search strings used to retrieve patent data

Lead acid battery search string

(IC=(H01M 4/14 or H01M-010/06 or H01M 10/08 or H01M 10/10 or H01M 10/12 or H01M 10/14 or H01M 10/16 or H01M 10/18)) or (EC=(Y02T001070B4 or Y02E006012F))
or
(TI=((batter* or accumulator*2 or (stor* and device*2) or cell*2) and (acid) and (lead)))

scheme	class	description
IPC	H01M-04/14	electrodes for lead-acid accumulators
IPC	H01M-10/06	lead-acid accumulators
IPC	H01M-10/08	lead-acid accumulators; Selection of materials as electrolytes
IPC	H01M-10/10	lead-acid accumulators; Selection of materials as electrolytes; Immobilising of electrolyte
IPC	H01M-10/12	lead-acid accumulators; Construction or manufacture
IPC	H01M-10/14	lead-acid accumulators; Construction or manufacture; Assembling a group of electrodes or separators
IPC	H01M-10/16	lead-acid accumulators; Construction or manufacture; Assembling a group of electrodes or separators; Suspending or supporting electrodes or groups of electrodes in the case
IPC	H01M-10/18	lead-acid accumulators with bipolar electrodes
ECLA	Y02E006012F	lead acid batteries
ECLA	Y02T001070B4	lead acid battery in transportation

Lithium ion battery search string

(IC=(H01M 4/13 or H01M 10/052 or H01M 10/0525)) or (EC=(Y02E006012B or Y02T001070B2))
or
(TI=((batter* or accumulator*2 or (stor* and device*2) or cell*2) and (li?ion or lithium)))

scheme	class	description
IPC	H01M-04/13	Electrodes for accumulators with non-aqueous electrolyte, e.g. for lithium-accumulators; Processes of manufacture thereof
IPC	H01M-10/052	lithium accumulators
IPC	H01M-10/0525	Rocking-chair batteries, i.e. batteries with lithium insertion or intercalation in both electrodes; lithium-ion batteries
ECLA	Y02E006012B	lithium batteries
ECLA	Y02T001070B2	lithium ion battery in transportation

Nickel battery search string

(IC=(H01M000432 or H01M000444 or H01M001030))
or
(((IC=(H01M000424 or H01M000426 or H01M000428 or H01M000429 or H01M000430 or H01M001024 or H01M001028)or EC=(Y02E006012D)) and TAB=((batter* or accumulator*2 or (stor* and device*2) or cell*2) and (nickel or cadmium or hydride or Ni?Cd))) not TI=(((lithium or lead) adj2 (batter* or accumulator*2 or cell*2)) not ((nickel or cadmium or hydride or Ni?Cd) adj2 (batter* or accumulator*2 or cell*2))))

scheme	class	description
IPC	H01M-04/32	nickel oxide or hydroxide electrodes
IPC	H01M-04/44	selection of substances as active materials, active masses, active liquids; alloys based on cadmium
IPC	H01M-10/30	nickel accumulators
IPC	H01M-04/26	electrodes for alkaline accumulator; processes of manufacture
IPC	H01M-04/28	electrodes for alkaline accumulator; processes of manufacture; precipitating active material on the carrier
IPC	H01M-04/29	precipitating active material on the carrier by electrochemical methods
IPC	H01M-04/30	electrodes for alkaline accumulator; processes of manufacture; Pressing
IPC	H01M-10/24	alkaline accumulators
IPC	H01M-10/28	alkaline accumulators; Construction or manufacture
ECLA	Y02E006012D	alkaline secondary batteries, e.g. NiCd or NiMH

Appendix C Results of regressions without truncating citations after 10 years and without granting a minimum citation window

	Dependent variable	DIRECTION Intra-technology knowledge flows	 Inter-technology knowledge flows	 External knowledge flows
Diversity of prior art (Hyp. 1a/b)				
Diversified knowledge	Techn. distant prior art	0.000	0.007***	0.094***
	Techn. related prior art	-0.002	0.401***	0.038
Specialized knowledge	Techn. near prior art	0.078***	0.003	-0.040***
Degree of technological centrality of knowledge (Hyp. 2a/b)				
Core Knowledge	Materials	0.221***	-0.284***	0.136
	Principal components	0.171***	-0.257***	-0.644***
	Cell system	-0.081***	-0.248***	-0.607***
Peripheral knowledge	Additional components	-0.162**	0.752***	1.118***
Controls				
	Battery type: Lithium-ion	1.230***	-1.437***	-0.431***
	Battery type: Lead-acid	0.048	-0.581***	-1.056***
	Triadic patent	0.757***	1.107***	0.808***
	Priority date	0.124***	0.142***	0.050***
	Priority date squared	-0.009***	-0.010***	-0.006***
	Mean backward citation lag	0.041***	0.073***	0.066***
	Constant	-0.283***	-1.772***	0.309***
	Overdispersion (ln α)	0.418***	1.572***	1.961***
	Number of observations (patents)	70448	70448	70448
	Log-Likelihood	-108822	-16786	-53218
	Nagelkerke Pseudo-R^2	0.37	0.22	0.19

10-year citation window data set; Negative binomial regression model with heteroscedasticity- and autocorrelation- robust standard errors; * p<0.1; ** p<0.05; *** p <0.01

Appendix D Correlation of independent variables

	The diversity of prior art (Integrated prior art)			**The degree of technological centrality of knowledge** (Product architecture)				**Controls**				
	Techn. near prior art	Techn. related prior art	Techn. distant prior art	Materials	Principal com-ponents	Cell system	Additional com-ponents	Battery type: Lithium-ion	Battery type: Lead-acid	Triadic patent	Priority date	Priority date squared
Technologically near prior art	1											
Technologically related prior art	0.1327*	1										
Technologically distant prior art	0.2888*	0.3977*	1									
Materials	0.0520*	-0.0018	0.0421*	1								
Principal components	0.0397*	-0.0421*	-0.0684*	-0.1924*	1							
Cell system	-0.0144	-0.0227*	-0.0456*	-0.0893*	-0.3379*	1						
Additional components	-0.0581*	0.0901*	0.1277*	-0.0692*	-0.2620*	-0.1216*	1					
Battery type: Lithium-ion	0.1173*	-0.0593*	-0.0277*	-0.0525*	0.0480*	0.0805*	-0.0603*	1				
Battery type: Lead-acid	-0.0989*	0.0153	0.0213*	-0.0650*	-0.0633*	-0.0127	0.0501*	-0.6092*	1			
Triadic patent	0.4103*	0.1742*	0.1989*	0.0826*	-0.0264*	-0.0314*	-0.0029	0.0133	-0.0484*	1		
Priority date	0.0973*	0.0407*	0.0210*	-0.0070	0.0187*	-0.0698*	0.0023	0.2212*	-0.1731*	0.0415*	1	
Priority date squared	0.0996*	0.0380*	0.0202*	-0.0025	0.0187*	-0.0676*	-0.0009	0.2110*	-0.1577*	0.0379*	0.9758*	1
Mean backward citation lag	0.3865*	0.1709*	0.2462*	0.0627*	-0.0227*	-0.0793*	0.0518*	-0.0440*	0.0198*	0.3293*	-0.0177*	-0.0119

10-year citation window data set; * indicates significance at 1% level;

Appendix E Results of regressions with relative measures for backward citations

		DIRECTION		
	Dependent variable	Intra-technology knowledge flows	Inter-technology knowledge flows	External knowledge flows
Diversity of prior art (Hyp. 1a/b)				
	Total number of citations to prior art	0.035***	0.023***	0.032***
Diversified knowledge	Share of techn. related prior art citations	0.020	2.194***	-0.255
Specialized knowledge	Share of techn. near prior art citations	0.789***	-0.957***	-2.101***
Degree of technological centrality of knowledge (Hyp. 2a/b)				
Core Knowledge	Materials	0.232***	-0.361**	0.025
	Principal components	0.044	-0.154*	-0.510***
	Cell system	0.061	-0.248**	-0.394**
Peripheral knowledge	Additional components	0.052	0.666***	1.142***
Controls				
	Battery type: Lithium-ion	1.016***	-1.181***	-0.721***
	Battery type: Lead-acid	0.095	-0.248**	-0.495***
	Triadic patent	0.815***	0.946***	0.927***
	Priority date	0.145***	0.245***	0.155***
	Priority date squared	-0.014***	-0.021***	-0.010**
	Mean backward citation lag	0.001	0.024	0.028
	Constant	-0.443***	-1.353***	1.036***
	Overdispersion (ln α)	0.112***	1.221***	1.704***
	Number of observations (patents)	10009	10009	10009
	Log-Likelihood	-25030	-5528	-13218
	Nagelkerke Pseudo-R^2	0.30	0.18	0.20

10-year citation window data set; Negative binomial regression model with heteroscedasticity- and autocorrelation- robust standard errors; * p<0.1; ** p<0.05; *** p <0.01

Appendix F Expert interviews

In total interviews with 12 battery experts from research organizations and industry experts were conducted (see Table below). Each interview lasted between 10 and 50 minutes. The interviewees were asked to first identify the different components relevant for the three battery types and second rank them regarding their centrality in terms of the hierarchy of control (cf. Murmann and Frenken, 2006). Components which are more central dominate the design of less central ones. The quotes below underline the number and ranking of hierarchy levels.

Table F.1: Overview of interviewees

Type of Institution	Location	Position	Expertise
University	France	Research Assistant	Battery manufacturing
University	Japan	Professor	Electrochemistry
University	Japan	PhD student (4th year)	Chemical engineering, hybrid storage systems
University	Switzerland	Professor	Electrochemistry (solid state)
University	Switzerland	Research Assistant	Stationary energy project analysis, storage cost modelling
University	USA	Post-Doc	Life-cycle analysis of energy storage technologies
Battery cell producer	Germany	Head of Operations	Battery design and manufacturing
Electronics producer	Germany/Japan	Head of procurement	Integration of battery technologies; costs and performance reviews of battery technologies
Battery project developer	Germany	Project manager	Selection of battery technologies and designs
System integrator	Switzerland	Head of battery research	Battery performance testing
Consulting firm	Germany	Consultant/industrial engineer	Battery storage analysis for automotive applications
Consulting firm	Germany/India	Principal	Battery industry structure and strategy

Regarding the **number of different hierarchy levels**, typically four different components were identified.

"In batteries, there is the chemistry, i.e. the materials, then there is the components in which the materials are processed, i.e. the anode, cathode and electrolyte. This is put in a cell concept. Finally this is packaged into a battery."

"The split in the four categories materials, principal components, cell system and additional components makes sense for the three battery types you analyze. The categories would look differently when analyzing flow batteries and other designs."

Note that two interviewees pointed out, that differentiating material and principal components might be tricky in the case of liquid electrolytes. However, for solid electrolytes (as used in most Li-Ion batteries), electrolyte material and design of electrolyte are two different choices.

"Apart from liquid electrolytes (where material and principal component are the same), the four proposed categories make sense."

Regarding the technological centrality of the component categories, the interviews clearly resulted in the following hierarchy of control (see selected quotes):

Material dominates all other categories

"The choice of the chemistry, i.e. material, dominates the design of the entire battery."

"Battery design starts with material. Only then the main components are analyzed and designed."

"The constitution of the electrodes will depend on the material choice."

"The material determines the structural design of the cathode, e.g., a LiTiS2 LCO cathode design is quite different compared to a LiMn2O4 cathode. The anode material determines the electric potential. Depending on that the anode is designed differently."

"When designing a battery, the material is selected first (e.g. LiMO) and principal component designs are then selected based on the material decision."

"Cell system layouts can differ. Their design depends on the material used."

"The design of the cell system follows the combination of materials used. The material determines electrical potential. This needs to be reflected by the cell design"

"The material influences cell system design, as e.g. the volume of the cell depends on the material."

"The material influences the design of the entire battery, even the additional components. For instance, the charger needs to be designed differently for different materials. Also cooling, as different materials develop different levels of thermal energy."

Principal components (anode, cathode, electrolyte) dominate cell design and additional components

"The cell system design depends on the principal components and their materials. Think of a liquid versus a solid electrolyte."

"The system layout is (re)designed after components are selected, in order to fulfill criteria like energy density, cycles, safety etc."

"The principal components determine the cell system design. For instance the electrodes' thickness impacts the cell design."

"Whether a liquid or solid electrolyte is used massively impacts the cell system design."

"The choice of principal components impacts the additional components. E.g., different electrode designs lead to different thermodynamics and thereby impacts cooling needs."

Additional Components – dominated by other three categories

"The additional components will be the last to be designed. They can be connected to different systems."

"Additional components are designed only after the three other levels are stable."

"The additional components typically do not impact the design of any of the three more central component categories."

Appendix G Notes on estimation technique

As the dependent variable, knowledge flows, is measured by the number of forward citations, i.e., count data, we employ the negative binomial regression technique (cf. Section 3.2.3). Alternative techniques for regressions on count data are the Poisson, the zero-inflated negative binomial, and the zero-inflated Poisson regression technique. Although all four regression approaches are Maximum Likelihood estimators, there are some important differences that guide the choice among them.

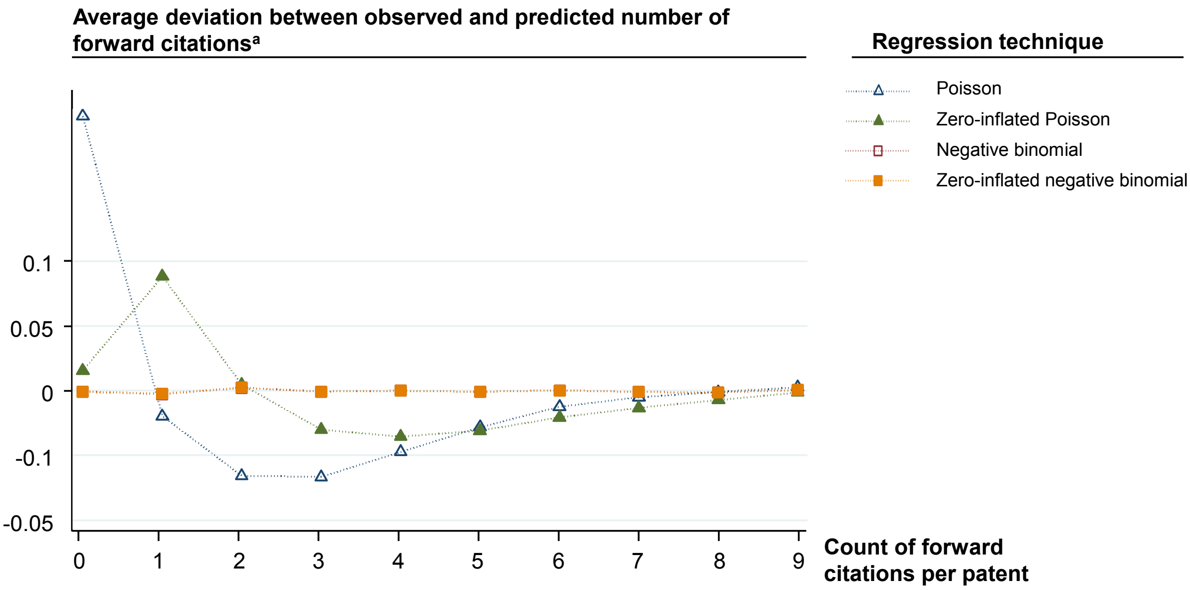
The Poisson distribution assumes a variance equal to the mean of the data, whereas the negative binomial regression technique relaxes this assumption. As the variances of the three dependent variables (Intra-, Inter-technology and External knowledge flows) exceed their means by far, the data can be described as over-dispersed, supporting the choice of the negative binomial model instead of the Poisson model.[1]

In case the dependent variable exhibits a high number of zeros, zero-inflated models can be used. These models allow for two distinct processes to generate the zeros when fitting the observed data and thereby increase the probability of zero counts. A test proposed by Vuong (1989) can be used to compare the fit of the standard negative binomial model and the zero-inflated negative binomial model. This test shows mixed results: For the regression on Intra-technology knowledge flows it supports the choice of the standard negative binomial model, while for the regressions on Inter-technology and External knowledge flows it supports the zero-inflated model. Consequently, we incorporate the zero-inflated negative binomial model as a sensitivity analysis in the results.[2]

Plotting the difference of the predicted and the observed number of knowledge flows shows evidence supporting the choice of the negative binomial and the zero-inflated negative binomial model. Figure A.1 shows that negative binomial models fit the observed data far better than the Poisson models.

[1] The Poisson distribution assumes a variance equal to the mean (equi-dispersion), whereas the negative binomial distributions allow for over-dispersion through the incorporation of the α parameter (Long and Freese, 2006). Tests for the significance of the α parameter reject the null hypothesis of equi-dispersion at a 0.1% significant level, strongly supporting the choice of the negative binomial regression.

[2] Zero-inflated models need a second set of explanatory variables to *inflate* the probability of a zero (Long and Freese, 2006). To this end, we use the binary variable *Granted* which indicates the legal status of a patent. (Conditional means of forward citation based on *Granted* show that granted patents have a higher probability of forward citations.)



[a] Positive deviations indicate underpredictions. Specification 1, regression on Intra-technology knowledge flows.

Figure G.1 Measure of fit across regression techniques

Appendix H Results of regressions on knowledge flows. Coefficients expressed as percentage change of dependent variable.

	Dependent variable	DIRECTION		
		Intra-technology knowledge flows	Inter-technology knowledge flows	External knowledge flows
Diversity of prior art (Hyp. 1a/b)				
Diversified knowledge	Techn. distant prior art	0.6%**	2.6%**	15.3%***
	Techn. related prior art	4.3%	59.5%***	6.8%
Specialized knowledge	Techn. near prior art	9.9%***	0.6%	-3.0%***
Degree of technological centrality of knowledge (Hyp. 2a/b)				
Core Knowledge	Materials	28.0%***	-34.9%***	-5.9%
	Principal components	11.9%***	-21.9%***	-52.1%***
	Cell system	6.7%**	-26.0%***	-57.9%***
Peripheral knowledge	Additional components	-10.9%**	90.3%***	266.0%***
Controls				
	Battery type: Lithium-ion	207.5%***	-71.2%***	-54.5%***
	Battery type: Lead-acid	-6.5%	-38.4%***	-60.9%***
	Triadic patent	101.6%***	163.6%***	171.1%***
	Priority date	16.4%***	28.6%***	9.7%**
	Priority date squared	-1.3%***	-2.0%***	-0.6%*
	Mean backward citation lag	9.8%***	20.6%***	24.7%***
	Constant	-0.699***	-2.543***	-0.637***
	Overdispersion (ln α)	0.228***	1.424***	1.921***
	Number of observations (patents)	22548	22548	22548
	Log-Likelihood	-45461	-8163	-20459
	Nagelkerke Pseudo-R^2	0.31	0.17	0.18

10-year citation window data set; Negative binomial regression model with heteroscedasticity- and autocorrelation- robust standard errors; * $p<0.1$; ** $p<0.05$; *** $p<0.01$

Interpretation:
Continuous variables: "For 1 additional (to the mean) backward citation to technologically near prior art, the expected number of intra-technology knowledge flows increases by 9.9% holding all other variables constant (at their mean)."
Binary variables: "Being a *Materials* patent increases the expected number of intra-technology knowledge flows by 28.0%, holding all other variables constant (at their mean)."

Appendix I Significance levels of Wald tests on difference of coefficients

	(1) Intra-technology knowledge flows			(2) Inter-technology knowledge flows			(3) External knowledge flows		
Diversity of knowledge	**Intra-technology knowledge flows**	**Inter-technology knowledge flows**	**External knowledge flows**	**Intra-technology knowledge flows**	**Inter-technology knowledge flows**	**External knowledge flows**	**Intra-technology knowledge flows**	**Inter-technology knowledge flows**	**External knowledge flows**
Intra-technology knowledge flows		insign.	****		****	insign.		insign.	****
Inter-technology knowledge flows			***			****			insign.
External knowledge flows									

	(1) Intra-technology knowledge flows				(2) Inter-technology knowledge flows				(3) External knowledge flows			
Technological centrality	**Materials**	**Principal components**	**Cell system**	**Additional components**	**Materials**	**Principal components**	**Cell system**	**Additional components**	**Materials**	**Principal components**	**Cell system**	**Additional components**
Materials		insign.	insign.	****		insign.	insign.	****		****	****	****
Principal components			insign.	****			insign.	****			insign.	****
Cell system				****				****				****
Additional components												

Two-sided Wald tests: H_0: coefficient A – coefficient B = 0; * p<0.1; ** p<0.05; *** p <0.01; **** p<0.001

References

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