

Using case data to calibrate simulation models: An innovation network for thin-film solar technology

Working paper

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Abstract

Purpose of the paper and literature addressed: Simulation can offer insight that helps researchers understand innovation networks. However, a challenge for researchers using simulation is the calibration of these models. Calibration uses real world data to establish the capacity of the model to simulate the outcomes of real world examples. This paper illustrates how “qualitative” case data can be used to extract information that can be used to calibrate a model of an innovation network.

Research method: The paper draws on data from a range of publically available sources; including case summaries, press releases, journal articles, reports and popular media to explore the development of a thin-film solar technology in Australia (and globally). These sources provide the evidence to develop inductive arguments that form the “rules” that are used to calibrate a simulation model.

Main contribution: The paper sets out a method for calibrating rules for fuzzy set theory models. In particular, it highlights the processes use for interpreting rules and the types of evidence that can be used to form the “rules” that describe an innovation setting. The paper provides researchers with a reproducible methodology that can be used in to calibrate fuzzy set theory models.

Keywords: *Innovation, Solar, Calibration, Fuzzy Set Theory, Case Study, Method*

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INTRODUCTION

A central factor in explaining innovation success is a business's capacity to access and use the resources within the broader network. However, "*while connectivity does matter to [innovation] performance and is important to master, it is at the same time difficult to shape*" (Rickne 2006, p. 405). This is because innovation networks are emergent phenomena. They are made up of interdependent organisations whose managers are each trying to accomplish their own goals whilst simultaneously responding to the actions of others (Wilkinson and Young 2002). This is the great challenge for innovation entrepreneurs, innovation agencies and theorist alike as current multivariate techniques do not model emergent behaviour within complex systems. In recent work, the case has been made for the use simulation to explore these types of complex adaptive systems (Herbert 2006; Oлару et al. 2009; Purchase et al. 2008). Simulation offers insight to complex adaptive systems because these techniques can deal with emergence, non-linearly and unpredictability (Lissack 1999; Maguire et al. 2006). One particular simulation method is fuzzy set theory. Fuzzy set theory incorporates ambiguity in model development. For detailed discussion on fuzzy set theory see (Zadeh, 1965; Oлару and Smith, 2005).

A challenge for researchers using fuzzy set theory is model calibration, which is required to ensure that the models developed reflect real world scenarios. Calibration is a process of using real world data to establish rules and model fit. That is, the development of model foundations that ensure it simulates the outcomes of real world examples. The process is not straight-forward. By and large the empirical data available for model calibration in innovation research is from case studies of innovation businesses and networks. The current lack of consistency in calibration processes is one of the main weaknesses in simulation modelling (Maguire et al., 2006). This paper takes a step towards overcoming the lack of detail on model calibration available within the social sciences by illustrating a method used for model calibration.

This paper illustrates how "qualitative" case data was used to extract information required to calibrate a model of an innovation network. After first briefly describing the fuzzy set theory and the role of case material, the paper goes on to describe the focal case in some detail. As the case is presented a second narrative is used to describe the systematic approach to "extract" data or inductive arguments that form the "rules" for model calibration in simulation. These dual narratives consider the objectives of the simulation, the types of data that can be used, the quality of the evidence that is required to formulate rules and the process that can be used produce the "rules" for calibration. The paper concludes with a brief discussion of the substantive case and some interesting insights about innovation that unpack the dependencies that confound the capacity to generalise about conditions for innovation success using existing case based methodologies. Please note this paper does not outline the results of running the fuzzy set theory model – just highlights methodological steps that can be taken to ensure consistent and thorough rule development that is inputted into the fuzzy model.

USING CASE TO CALIBRATE SIMULATION

Fuzzy set theory is a methodological approach that can incorporate the characteristics of natural language—with its imprecision, uncertainty, incompleteness, vagueness (Nguyen and Walker 2000; Petrovic-Lazarevic 2001; Zadeh, 1965). It also allows for qualitative perceptions to be incorporated in models (Kvist 2007). Thus simulation hybridised with fuzzy set theory is an ideal approach when empirical evidence is case-based and qualitative.

There is a well established role for case data to provide evidence of the correspondence between the “real world” and any simulation of that “reality” (Maguire et al. 2006). Calibration is a process of using “real world” data to adjust and develop simulation rules such that the models developed as built on “real world” scenarios. The calibration process outlined in this paper uses case data within the calibration process. Case data has the advantages of enabling the researchers to look at the complexities of the interactions between multiple constructs over different time periods.

Prior to collecting case data, it is essential that careful consideration be given to the objectives of the simulation for which calibration data is required. Here, the overarching goal of the simulation is to understand the network conditions that impact the performance of radical innovations. Our simulation model incorporates a number of variables—types of actors, proportion of actor types, the level of knowledge and financial resources within the overall network, the relevance of knowledge resource exchange and relationship strength—as key explanations for innovation outcomes including knowledge and financial resources (Denize et al., 2007).

The process to extract the “rules” for calibration begins with the *elaboration of the context for the simulation* and the *a priori specification of simulation variables*. It is essential that these are established prior to selection of the case and the collection of case data as they provide the necessary frame for determining relevant case studies and the framework to guide the collection of source data. Therefore the context of the case is radical innovation process that incorporates multiple actors and the exchange of relational, knowledge and financial resources.

CASE SELECTION

The case chosen considers the innovation of thin-film crystalline silicon on glass (CSG) photovoltaic (PV) solar cells in Australia during the period 1985-2005 in Australia (and internationally as the case develops). Thin-film CSG technology enables the production of a robust solar cell that is not damaged by sun exposure and which during pre-production testing set international benchmarks for solar conversion efficiency. The case considers the innovation and commercialisation story from the perspective of three main actors, two businesses (Pacific Solar P/L, CSG Solar Australia P/L) and a University (University of New South Wales) which have had a central role in the development and commercialisation of this technology. This case “fits” the simulation context—it is a radical innovation. We also noted that there was a considerable body of information regarding the development of this innovation.

DATA COLLECTION

The case description summarises publicly available information regarding the commercialisation of the CSG PV solar cells and in particular draws on various reports and case summaries published by government/s and government departments and in journals, press releases and popular media reports and company websites. This data was collected in

an extensive internet search using a range of key words including (i) technology names and variants (e.g. thin-film photovoltaic cells, crystalline silicon on glass, CSG, PV etc); (ii) company and organisation names (e.g. Photovoltaic Centre of Excellence, Pacific Solar, CSG Solar etc.) and (iii) the names of key individuals involved in the research and commercialisation process (e.g. Martin Green, David Hogg etc.). A crucial consideration at this stage of the data collection is to employ search strategies that produce maximal outputs.

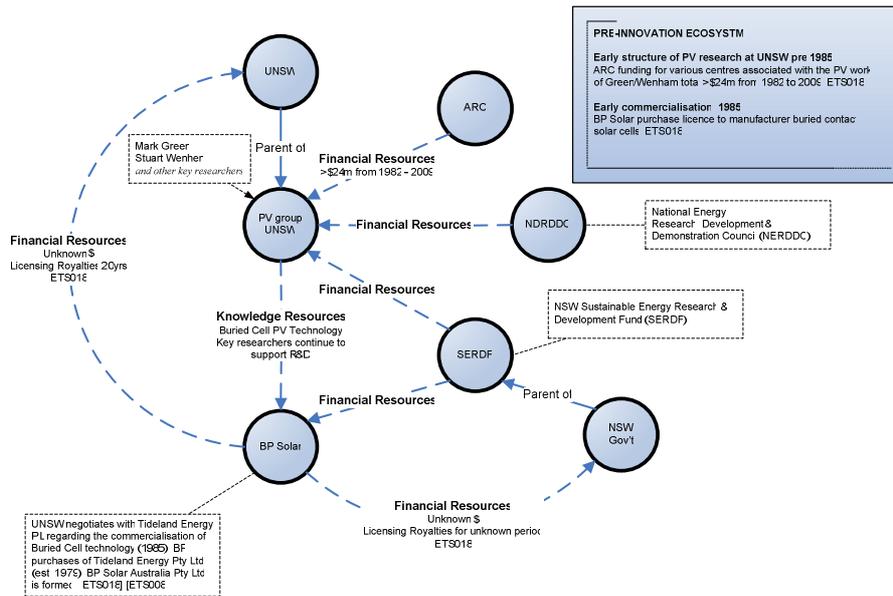
This research produced a wide range of different types of documents, ranging from research reports and journal articles describing the technology to reports and information that described aspects of the innovation process, the actors and activities involved. Initial data pre-processing required the filtering (excluding) data which exclusively focused on the technology and the science (compared to the innovation process). This data was eliminated from further analysis as it did not relate to the focus within the simulation model. For example, excluded data included the types of experiments conducted, the chemical processes used to create the thin film etc. In this context, details of the technology were only relevant to the extent that it could be used to assess the “novelty” of the innovation.

DATA COLLECTION AND SUMMARY

Throughout the case description references to source documents are provided in square brackets, viz. [ETS018] is a report on the commercialisation of Photovoltaics research in Australia by Muriel Watt for a government department in 2003. A listing of source documents are available from the researchers upon request. Modified narrative event sequencing (Buttriss and Wilkinson 2006) was used to identify critical points in the history of the focal case. These critical events are summarised below and provide a framework for constructing a story around the focal case. The *identification of critical events* is the next step in constructing simulation “rules” from case based data. These key events are now considered.

CSG technology was initially developed in Australia by researchers at a leading university [ETS025]. This second generation solar technology was developed by an established research group which had previous successes with buried-cell technologies. In the early 1990s staff at the UNSW School of Electrical Engineering had established an international reputation for their research in PV technologies and were successful in obtaining ARC funding to establish a research centre—the Centre for Photovoltaic Devices and Systems (1991-1994) [ETS024]. At that time the Centre had already had an operational pilot line for the fabrication of buried contact solar cells and had licensed the technology to BP Solar Pty Ltd some years earlier (1985) [ETS018]. During 1992, Unisearch Pty Ltd (an entity wholly owned by UNSW) had commenced marketing the buried contact cells produced by the pilot line [ETS024]. The successful commercialisation of this first phase of PV research created a strong revenue stream upon which further research could be built. This included the work on CSG thin film technologies. The snapshot ecosystem for this early pre-innovation organisation is shown in Figure 1. Figure 1 displays the major players influencing the development of thin-film technology from 1985 to 1994.

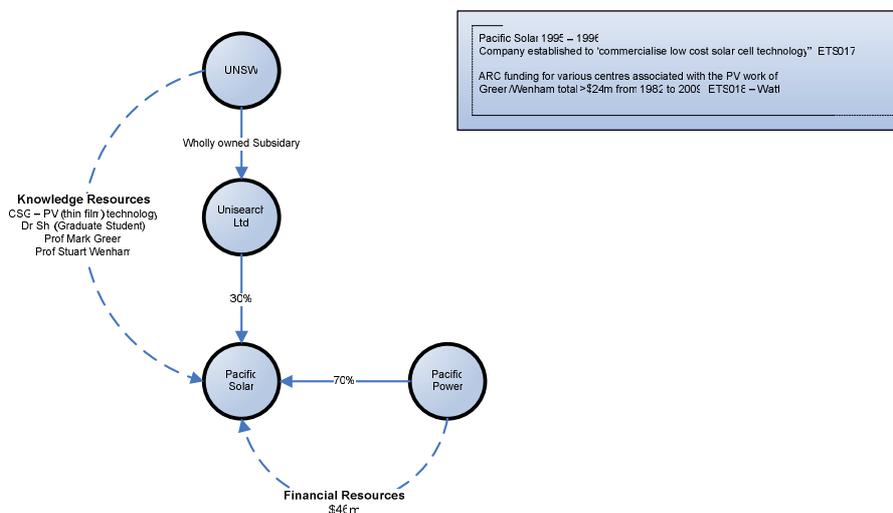
Figure 1: Pre-innovation network (1985-1994)



During this pre-innovation period the researchers gradually increased research efforts on thin film PV technologies. By 1992, centre researchers (Professor Martin Green, Dr. Stuart Wenham and Dr. Zhengrong Shi, among others) were working on optimising procedures for the fabrication of CSG PV cells (for which proof of concept had previously been established) [ETS024]. The University had a strong focus on technology transfer and in 1995 a spin-off company (Pacific Solar Pty Ltd) commenced operations. The company was jointly owned by Unisearch Ltd (30%) (a wholly owned subsidiary of the University of New South Wales responsible for technology transfer and commercialisation) and Pacific Power [ETS023].

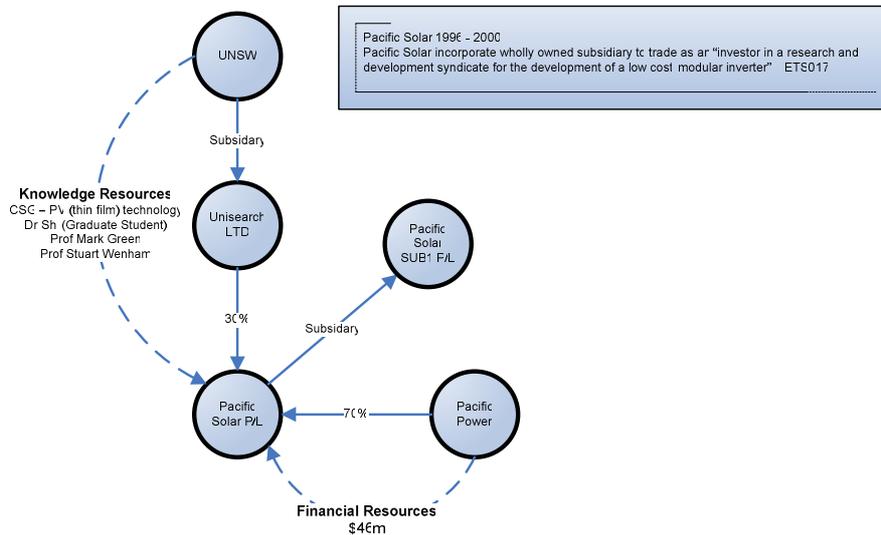
During this same period the research group at the University of New South Wales had become a special research centre funded by the ARC. Pacific Solar P/L maintained strong links with the researchers by engaging the Centre for contract research and many of the Centre staff were seconded to the company to assist with developmental research [ETS025]. This first stage in the development of the thin-film CSG PV technology is shown in Figure 2.

Figure 2: Development Network (1995 – 1996)



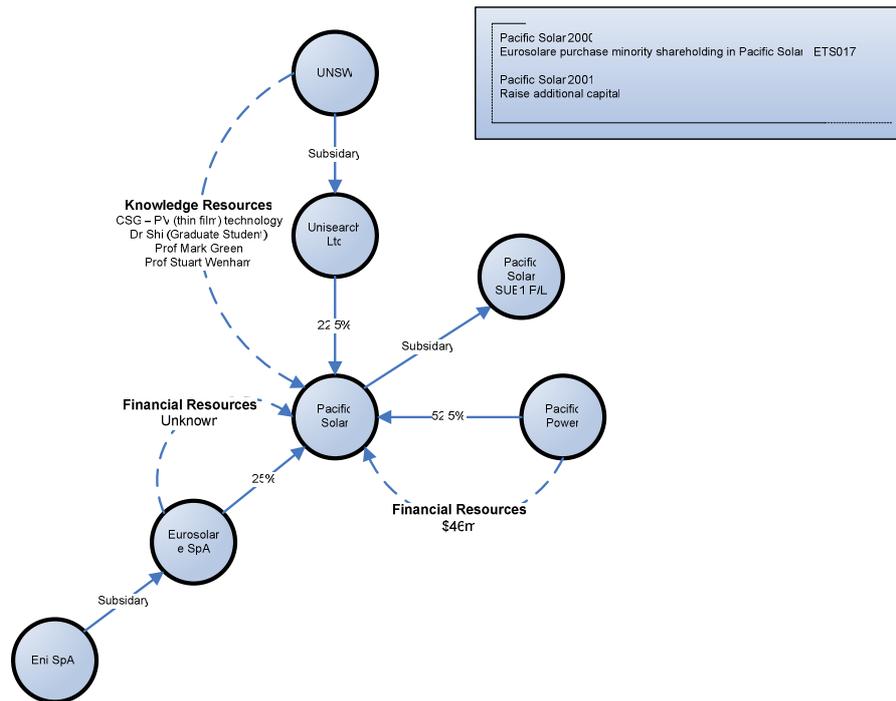
Recognising that complimentary technologies would be essential to the commercialisation of the CSG-PV solar cells Pacific Solar established a wholly owned subsidiary to develop a low cost modular inverter [ETS017]. This subsidiary later proved to be crucial as the modular inverter created a revenue stream for Pacific Solar. To create this revenue flow the inverter was actually used with first generation buried cell solar panels made by BP solar. Figure 3 shows the development of the early commercialisation network.

Figure 3: Early Commercialisation 1 Network (2006 – 2000)



The funding provided by Pacific Power (a state owned utility company) was crucial to the early commercialisation of the CSG technology. However access to further funds from this government source was limited. By 2001 Pacific Solar needed further capital to fund the ongoing development and commercialisation of the CSG technology. Eurosolar SpA (a subsidiary of the Italian energy conglomerate Eni SpA) purchased a 25% holding in Pacific Solar. At the time Eurosolar SpA had a 5 MW operating capacity and the investment in Pacific Solar was viewed as strategically significant [ETS012]. Not only did Eurosolar SpA become the European distributor for the modular inverter [ETS035] but the investment provided important public confirmation of Eni SpA interest in environmentally sustainable energy solutions [ETS012]. Figure 4 shows the network for ongoing commercialisation of the CSG technology.

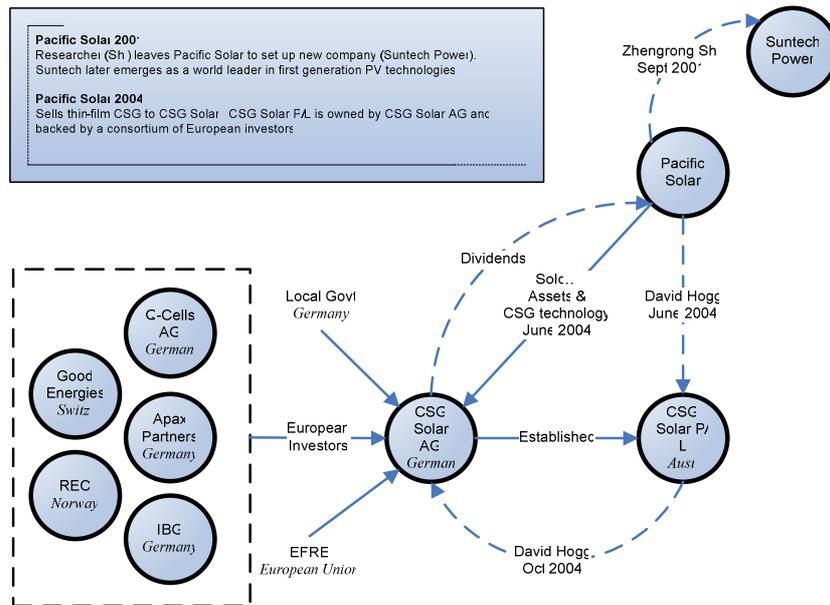
Figure 4: Early Commercialisation 2 Network (2000 – 2001)



In 2001 one of the key research team (Shi) had left the University of New South Wales and his role in Pacific Solar. This post-doctoral researcher subsequently went on to establish what is today one of the world's largest manufacturers (Suntech) of solar panels (using first generation technology) [ETS001].

Commercialisation work continued at Pacific Solar however it was becoming clear that a considerable further investment would be required to fully commercialise the technology. In 2004 Pacific Solar sold the rights to the CSG technology to CSG Solar P/L a wholly owned subsidiary of CSG Solar AG. David Hogg, (previously from Unisearch Ltd and the Managing Director at Pacific Power) joined CSG Solar P/L as part of the management team. Over twenty former employees of Pacific Solar owned a substantial share of the new company. Shortly after joining CSG Solar P/L, Hogg moved to Germany to take up a senior management position in the parent company. This final "mature" commercialisation network is shown in Figure 5.

Figure 5: Mature Commercialisation 3 Network (2004)



CGG Solar AG was backed by a consortium of European investors who were themselves either directly involved in solar cell production or interested in sustainable energy production. The company also had financial support from Land Saxony-Anhalt (local government) and from the European Union European Funds for Regional Development (EFRE) [ETS003]. CSG Solar AG continued the development of the thin-film technology and by 2006 had commenced mass production of thin-film CSG cells and reached the milestone of 24/7 production in 2007 [ETS004]. By 2008 the company was producing 13 MW per annum [ETS039]. However, by the end of the year the company had closed the manufacturing plant and laid off a substantial proportion of their workforce [ETS045].

CLARIFYING RULES

As mentioned a modified narrative event sequencing approach was used to identify critical events in the history of the case. These critical events provide useful “vignettes” of the case at a point in time. After *classifying case material by each “event”* it is then *coded according to its relevance to particular simulation variables*. We examined the case data and identified material that pertained to each of the input variables. Next the *material was coded according to the permitted values for the relevant variable*. To illustrate consider a commonly used descriptor of relationships in business and innovation settings—relationship strength. Relationship strength may reflect and be reflected in things such as commitment ((Sharma et al. 2006; Skarmeas et al. 2002), trust (Young 2006), and social capital (Baron and Markman 2003; Burt 1997; Cooke and Wills 1999). Relationships may be characterised as strong or weak however it clear that the boundaries of such descriptors are vague. To handle this ambiguity we have *arbitrarily delineated three values/adjectives* that describe relationship strength; low, medium and high. This was done prior to the calibration phase and was part of the original specification of the simulation model (reference removed for review).

Table 1 provides a summary of the evidence drawn from the case for a particular event—the formation of Pacific Solar P/L, as per figure 2.

Table 1: Evidence from the case (critical event 1995-96 during the formation of Pacific Solar P/L)

Variable	Permitted Values	Evidence from Case	Assigned Value
Type of actor (central actor) Main role	CRISP VALUES 1=FB 2=M 3=RD	Evidence from the perspective of Pacific Solar P/L R&D: UNSW-PVC, PS OWNER: UNI:PP [70:30 equity] FB: PP	R&D
Number of R&D	RANGES [0-1] = LOW [1-2] = MED [2 -) = HIGH	2	HIGH
Number of manufacturers	RANGES [0-1] = LOW [1-2] = MED [2 -) = HIGH	0	LOW
Number of financial backers	RANGES [0-2] = LOW [2-4] = MED [4 -) = HIGH	1	LOW
Amount of financial resources	RANGES [0-1] = LOW [1-2] = MED [2-3] = HIGH	Pacific Solar commenced operation in February, 1995 as a \$64 million collaborative venture between Pacific Power and Unisearch Ltd. [ETS023, p32] ; cf Investment in the company by Pacific Power totalled \$46.0 million when a final equity funding option was exercised during 1999. [ETS017, 2001, p198]; Funding for the first five years of Pacific Solar was provided entirely by Pacific Power. [ETS006, 2008]; Pacific Power's investment in Pacific Solar was key to its establishment. Setting up a company opened up opportunities for capital raising that are not available to research groups. Nevertheless, because Pacific Power was government owned, Pacific Solar's access to further government R&D funding has been restricted. [ET018, 2005, p26]	LOW
Product Knowledge (amount)	RANGES [0-1] = LOW [1-2] = MED [2-3] = HIGH	Crystalline Silicon on Glass (CSG) technology patented by the UNSW PV Centre which was assigned to Pacific Solar in return for a 30% UNSW shareholding in the company. [ETS018, 2003, p17]	HIGH
Novelty Product Knowledge (relevnace)	RANGES [0-1] = LOW [1-2] = MED [2-3] = HIGH	One area pushes at the leading edge of energy conversion efficiency, with little regard for ultimate device cost. The purpose is to identify, understand and overcome present energy conversion efficiency limitations. The second area seeks to incorporate new knowledge, gained in the first area, into devices that are currently commercially relevant.	HIGH
Relationship strength	RANGES [0-1] = LOW [1-2] = MED [2-3] = HIGH	[PS-PVC] The new company is leasing the Centre's Bay Street facility from the University and is engaging the Centre's services for contractual research. Additionally, a number of Centre staff have been seconded from the Centre for the duration of the company's developmental phase to assist in meeting the company's objectives.[ETS024, 1996, p32]	HIGH
Change (output variable)	RANGES [0-0.66] = LOW [0.66-1.34] = MED [1.34-2] = HIGH	Pacific Solar established a PV systems arm to develop a market presence for its CSG technology. It has developed PV module-integrated inverters, modular rooftop mounting supports and balance of system components for use in its Plug&Power TM rooftop PV systems. [ETS018, 2003, p18]; [GENERAL] With these unfavourable market conditions, PV is not yet a highly profitable technology [ETS018, 2003, p24] No financial return but with the commercialisation of the "plug and power" modular inverters (complementary research) new knowledge has been generated.	Financial LOW Knowledge MEDIUM

The table shows the evidence and the corresponding assigned value for each variable. As a point of comparison, the permitted values that were developed a priori (based on theory) are also provided. The two rule/s developed from Table 1 are:

- If {actor = R&D} AND {number of R&D = high} AND {number of manufacturers = low} AND {number of FB = low} AND {amount of financial resources = low} AND {amount of product knowledge = high} AND {novelty of product knowledge = high} AND {relationship strength = high} THEN {change in financial resources = low}
- If {actor = R&D} AND {number of R&D = high} AND {number of manufacturers = low} AND {number of FB = low} AND {amount of financial resources = low} AND {amount of product knowledge = high} AND {novelty of product knowledge = high} AND {relationship strength = high} THEN {change in knowledge resources = medium}

To increase the reliability of the “value” assignment this work was undertaken by one member of the research team and then subsequently reviewed by a second member of the team. The above example of rule development was then conducted for each scenario developed from the case data. Currently, 27 scenarios have been developed which has resulted in over 300 rules being developed. Given that assigned values can be more than one (for example low and medium) then each scenario generates multiple rules depending on the assigned values.

Once the rules were developed then the researchers went through and investigated if there were missing scenarios that still need to be included. For example scenarios that did not occur within this case but have been shown to occur in previously published literature. This step is important for ensuring that the model is generalisable to the wider context of radical innovations. Rules for the missing scenarios were then developed from case published in the literature.

However, it is noted that a further benefit of fuzzy simulation models is their robustness and their capacity to handle “vagueness” in the calibration rules (Nguyen and Walker 2000; Petrovic-Lazarevic 2001). This is because fuzzy simulation models draw on multiple “events” to fully calibrate the model. Thus the final stage of the process involves collecting a number of different events to maximise the variation across each of the variables. That is, selected calibration events should reflect a variety of different variable/level combinations.

In summary, we note that following key steps in extracting “rules” for calibration from case-based data:

1. Elaborate of the context for the simulation
2. Specify (a priori) the simulation variables and values
3. Establish data search criteria
4. Identify the boundaries for excluding information
5. Identify critical events
6. Classify case material by “event” and relevance to particular simulation variables
7. Assign values to reflect the “rules” for calibration

DISCUSSION

The case itself is interesting because despite considerable investment and compelling evidence of strong network capabilities among network members—both considered key factors in innovation success—the innovation has not yet been successfully commercialised. The case suggests that the capacity of the broader innovation network to develop complementary technologies, the complex interaction between the innovation partners and other environmental factors are also crucial factors in innovation performance. This insight enabled the researchers to extend the simulation model to include complementary technologies and the simulation environment as key input variables.

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