TOWARDS A FRAMEWORK FOR EVALUATION OF RENEWABLE ENERGY STORAGE PROJECTS: A STUDY CASE OF HYDROGEN AND FUEL CELLS IN DENMARK

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ABSTRACT

Renewable energy is characterized by its intermittency and a general dislocation between places of production and places of use. To overcome the intermittency, renewable energy storage (RES) is critical in the design of a future carbon-free society. More than 700 RES projects are in the pipeline worldwide, and market potentials are projected as immense. RES is complicated, and projects persistently fail to present operational scale of operations except for a few "classical" storage technologies: Variants of lead-acid batteries and pumped hydro-power reservoirs. Most RES projects are relying on governmental subsidies or high-risk venture capital. RES projects are along the energy agenda following an agenda of industrial development. This paper discuss and develop a theoretical and empirical framing of RES within energy security, a distinct technological focus, knowledge creation and industrial and social agendas.

Keywords: Cleantech, business development, innovation management, energy systems

INTRODUCTION

One of the most capital intensive research areas of the 2010ies is renewable energy and especially renewable energy storage (RES) (Akinyele & Rayudu, 2014) with more than 700 projects worldwide (Cleantechnica, 2014; Pernick & Wilder, 2013). Most forms of renewable energy are of intermittent character and times of high production and low consumption must be balanced with times of low production and high consumption (Conolly, 2010; Ekman & Jensen, 2010; Hemmes et al., 2012; Martin & Grasman, 2006). Without RES, renewable energy will persistently fail to provide a secure, fossile-free economy especially within areas of energy for industrial processes, public services and transportation. RES must compete with fossile energy that is regarded as easy to store with a high energy density in form of coal and liquid carbon-hydrates (Geovanni et al., 2010; Ajanovic, 2008).

Research in RES particularly within hydrogen and fuel cells seems to be of high-risk and absence of clear technological trajectories (Geels, 2005). High-risk is associated with a general absence of core technologies, i.e. the RES research must create its own core technologies involving fundamental systems, electricity interconnections (Winkler-Goldstein & Rastetter, 2013). Risk is also coming from the expectation that RES must be possible to include in the energy system at production scale which means that units in the scale of kilowatt hour (kWh) are less relevant than larger units in megawatt hour (MWh) scale. The production magnitude is inducing cost of scale on the research that do have difficulties in exploiting knowledge gathered at smaller scale laboratory research and do have to solve new issues created from upscaling of technologies (Gallagher et al., 2012; Jacobsson & Bergek, 2003). Given the absence of proven technologies, there are little or no direct benchmarks for a technological trajectory and limited experience in given strategic direction to the research.

In this paper, the Danish initiatives on hydrogen and fuel cells will be used to establish an explanatory framework for the difficulties facing RES (EUDP, 2014; Hydrogennet, 2014; Energistyrelsen, 2004). The overall thematics can relate to several strands of management of technologi (de Oliviera & Fernandes, 2011; Schilling, 2010; Tambo, 2011; Tambo, 2012; Tidd et al., 2005). Firstly, the quest to lower the global carbon footprint needs credibility and credible technological solution, RES should establish the decisive factor of credibility to two leading renewable energy solutions: Photovoltaics (PV) and wind turbine generators (WTG) (Delucchi & Jacobsson, 2011; Geovanni et al., 2010; Züttel et al., 2010). Secondly, RES can serve as an excellent case in a combined, large scale, global effort to create new technologies; however, the extant number of projects not learning from the experience of other, testing questionable technology, testing existing, but not future technologies, and sometimes speculative character, is an fine scene of learning for management of technology (Tambo & Enevoldsen, 2014; Balachandra et al., 2010). Third, much of investments in RES as other research in renewable energy solutions, green technologies and cleantech are expected to provide an impact on industrial growth; this is not happening very often, which in-turn leads to controversy especially governmentally funded research failing to provide results (Bulathsinhala, 2013; DOE, 2005; Wanger & Leydesdorf, 2013).

The research question for this paper is: What are the key elements in an assessment framework for renewable energy storage technologies that can be derived from the experiences of the Danish initiatives on hydrogen and fuel cells?

The RES assessment framework is to follow the structure given above of, (1) the necessity to store fluctuant energy, (2) the learning for the cleantech industry, and (3) the existence of an industrial agenda.

THEORY

Renewable energy storage

The RES technologies are covering a wide spectrum of scientific and engineering disciplines (Akinyele & Rayudu, 2014; Conolly, 2010). RES can be mechanical, pneumatic, chemical, kinetic, potential, electrical, gaseous, solid, liquid and any combined hereof. Transformative solutions are seen e.g. when adding of hydrogen from wind turbines to biogas create a better gas (Braga et al., 2013; Hansen & Nybro, 2012; Buchhorn, 2007). The storage of electricity is mainly seen in batteries. Batteries can be different forms of lead batteries, light metal batteries typically using Lithium, and more novel fundamental battery types that hasn't left the laboratories yet. With the emergence of the idea of the Hydrogen society, hydrogen was expected to serve as a store media for electricity that would be produced in hydrolysers, stored in high pressure tanks, and fed into fuel cells are appropriate times (on-grid) (Geovanni et al., 2010; Jørgensen & Ropenus, 2008; Marban & Valdes-Solis, 2007; McDowall & Eames, 2006; Mulder et al., 2007; Schoenung, 2011). Hydrogen is also predicted to be used as fuel in cars (forecourt), or used in remote location as diesel substituent (off grid).

The hydrogen production has been associated with various problems, e.g. a relative low energy density unless with is highly pressurised, need for large, expensive tanks, safety issues, loss of energy in both the power supply, the hydrolyser, and in the fuel cell (Bičáková & Straka, 2012). A number of more complex measures have been suggested, e.g. convert hydrogen to methanol using atmospheric CO2 (Bockris, 2010; Boretti, 2013)

Theory of research and technology management

Clusters of entrepreneurs in the cleantech sector forming Technological Innovation Systems (TIS) are described by Bergek et al. (2008) that furthermore calls for creation of legitimation and 'secondary' effects, positive externalities, as a main objective of the TIS. Gallagher et al. (2012) define an Energy Technological Innovation System (ETIS) that require governance in the form of (1) distinctive and urgent tools for measuring the relationship between input and output (2) tools for assessment of appropriateness of technologies, and (3) governmental oversight mechanisms. This is implying that ETIS is characterised by imbalances in governance structures. In a Danish policy recommendation report (EUDP, 2014) is recommending continuously to prioritise a wide array of known technologies even if none of these have proven operational after 10 – 20 years of research.

In discussing key stakeholders and leaders in technological transformation in the energy sector, the TIS can be traditional key players as well as newcomers often across traditional lines within the industry and as such there exists blurred lines between industry actors (Curran et al., 2010).

Technological innovations do normally have to interact closely with entities of the society in socio-techical processes that cover the breadth of single factors and factorial interrelations determining the outcome of the innovation (Schot & Geels, 2008; Geels, 2005). In the energy sector such processes are prolonged and fundamentally longitudinal due to capital binding and spending requirements and technological inertia (Orrt & Dedehayir, 2010).

Due to the immense societal impact of changes in the energy sector, governmental interventions are commonplace (Ruegg & Thomas, 2009). The governmental role introduces different motives than the strictly commercial and can follow e.g. an industrial growth agenda, act as subsidies, teaching/ training, promote higher education (Brown & Hendry, 2009).

In several contexts, venture capitalists (VC) operate alongside governmental initiatives and research needs adaptive processes if should be engaged, especially the ability and credibility to create plans for maturing and commercialisation of the technologies at any level (Bürer & Wüstenhagen, 2009) both for technological products but also associated business models (Loock, 2012; Wüstenhagen & Menichetti, 2012). The cross-over from technology to business model innovation seems fundamental RES but greatly overlooked in governmentally funded projects (Chaurey, 2012; Richter, 2013; Richter, 2012; Brown & Hendry, 2009; Bulathsinhala, 2014).

Research assessment frameworks

There are several ways of assessing research. Within academic research it is publication and citation that is guiding (Konur, 2011). In fundamental and applied industrial research, the guiding principle is the research' ability to further technologies that can be converted into business models (Loock, 2012; Richter 2012; Chaurey, 2012). Considering RES as early stage research, research assessment frameworks must be able to encompass a relatively long timeline of prospective and experimental approaches and ending with the ability to create cost-effective and societal acceptable solutions.

DOE (2005) states that energy research need to be evaluated from perspectives of

- Uncertainty about the technological outcome of a program.
- Uncertainty about the market acceptance of a technology.
- Uncertainty about future states of the world.

OECD (1997) depicts research evaluation as a matter of targeted selections of evaluation approaches:

- Specific levels in the research system
- Selection of evaluator: Internal or external
- Hardship in creating output and outcome variables
- Approach: Quantitative methods leading to qualitative decisions
- A clear link between research evaluation and policy making

The International Energy Agency (IEA) emphasize that technologies will require governmental intervention and regulation at any point during its lifecycle with grants and funding at early stages, tax initiatives at later stages and market and energy security regulation in operational stages. Along this timeline also positive interaction between government, industrial actors, venture capitalists and capital markets is needed. Market pull is in the end the single most determining factor (Chiavari & Tam, 2011).

To further elaborate on the assessment factors, the literature is suggesting a breadth of issues and concerns. Below is presented a review of a range of contributions to assessment frameworks. The contributions are generally agreeing on the interrelation of factors ranging from technology to social issues.

Contributor	Energy security	Technology	Knowledge creation	Social and societal aspects
Sovacool (2013)	Availability, affordability, efficiency, sustainability			
Tijssen (1992)			Interdisciplinarity and cross-discipline synergy	
Akinyele & Rayudu (2014)		Discharge and capacity of RES		
Gallego et al (2010)	Continuity, conflict-risk			Political stability, risk management, quality of life
Chiavari & Tam (2011)	Coherent policy		Collaborativeness	Strategic processes
Clausen et al.		Matter		Economy

Contributor	Energy security	Technology	Knowledge creation	Social and societal aspects
(2010)		conversion effectiveness		
Delucchi & Jacobsson (2011)		Adherency to wind, water, sun		Economy
Edler et al (2012)			Collaborative learning	Demand focus
Gallagher et al. (2012)			Innovation system creation	Policy making, private sector focus
Hoffman & Jorgensen (1977)		Process analysis		Econometry
Jacobsson & Bergek ()		Availability of resources	Diffusion of knowledge	Formation of markets
Konur (2011)			Scientific records	
Kølsen et al. (2009)		Continuous reviews, effect analysis, innovation risk-willingness	International partners, teaching materials	User-driven innovation, leadership
Muir & Williams (1994)	Cross-project comparison	In-depth feasibility analysis testpoints		Higher precision in governmental research spending
Rao & Kishore (2010)			Technology diffusion	
Sovacool (2009)	System transformation			Designing politically driven incentives
Stephens et al. (2008)				Socio-political drivers as decisive
Züttel et al. (2010)	Hydrogen in energy security	For maturing of hydrogen technologies		

Theoretical perspective

A theoretical perspective for analysis of RES projects must account for previously mentioned agendas of energy system transition, the general aspects of the cleantech industry, and the industrial development expectation. Theoretical perspectives will have to ensure general scientific, technological and industrial feasibility. Advantageous is to establish a general supply chain perspective, where the RES is reviewed in a commercial and technical context of operational potentials and derived positive and negative contributions.

METHOD

The studies behind this paper comes out of the scientifically-based interest to obtain a better and deeper understanding of evaluation of cleantech research projects in respect to business development and alignment between operational systems and business model opportunities. The methodology is inspired of the interpretive and social thinking adopting a position like Mathiassen and Nielsen (2008), Lee (1989) and Walsham (1995). A critical observation is used in the studies of the perception of new technology as problem solver (Grant et al 2006, Davis et al. 2009), and the limitations of "traditional" distinctive research versus a broader understanding (Doucet et al 2009).

The method applied in the study of this paper is based qualitative and interpretive studies with research representatives (Klein & Myers 1999). It is based on the information system tradition of observing and understanding technological development within its context in organisation, application and business (Mathiassen and Nielsen 2008, Kock 2007). MOT is viewed as concurrent paradigmatic approach organised to study objects of the organizational context at both management and operational levels (Schultz & Hatch 1996).

The case is observed during 2013 and 2014 using project meetings, research design processes, and application analysis. This is furthermore supported with interviews and meeting observations with stakeholders and open sources such as websites, press releases, advertisements, and supplier information.

Methodological, the area is highly dependent on aggregate and varied methods ranging from techno-anthropology to very precise technical assessments. The area is characterised by many "beliefs" and is quite politicised with developmental struggles, clashes of technology (PEM vs alkaline), randomness of choice, and occasionally wizardry in the form of coincidential and strongly empirical results without theoretical considerations and documentation.

ENERGY TECHNOLOGICAL RESEARCH CASES

Denmark has been front-runner in several initiatives on "greener" energy supply. From the 1970ies district heating proliferated using combined heating and power generation (CHP) largely improving effectiveness. In the 1980ies large parts of the energy system was converted to natural gas and micro-CHP. In the 1990ies wind turbine generators (WTG) started to gain momentum as a response of sustainability. In the early 2000s offshore WTG took speed especially connected to megawatt-scale WTG's. Management of intermittency and fluctuations in the energy system was first regulated by rapid traditional power plants, later on the surpluses and deficits has been exchanged with neighbouring countries using financial instruments.

The Danish research in RES has been concentrated on hydrogen and fuel cells as energy storage technologies. With more than 32% of the overall electricity supply coming from WTG, the ability to store and retrieve is expected to be fundamental although until now not utilised in any way.

Hydrogen and fuel cells have been a distinct research priority since the late 1990ies. From 1997 to 2013 the hydrogen and fuel cell area has received 350 mill. USD in governmental support and research grants. This has created approx. 10 smaller companies and one business unit in a larger company. The companies are typically entrepreneurial, focused on early as well as late-stage research, demonstration projects and feasibility studies. Recent research review has critised the inability within this industry to convert research to commercial opportunities.

Most activities have been focused on fuel cells. Less, but more substantial processes have been focused on conversion of electricity to hydrogen. The RES projects have been “end-to-end”, including

- Modelling of supply side power
- Power supply and power conditioning for hydrolyzing
- Control systems for power supply and hydrolyser
- Hydrolyser technologies including electrodes, membranes, cell stack unit design
- Pumps and compressors
- High pressure storage
- Demand side management
- Development of business models

The Danish efforts have been complicated. During the 17 years of research granting, there hasn’t been created any commercially sound companies, maybe except one. Mid-2014 the larger company’s business unit was decided to be closed with a loss of governmental grants of 50 mill USD and 170 mill of the companies own investments. Meanwhile have a major part of the remaining companies restructured and mostly reduced expectations and staffing.

In the Danish context, high pressure alkaline hydrolyser technologies have been dominant for production of hydrogen. This technology has many advantages over low pressure alkaline hydrolysers and other technologies, however, in a broader scale, the technology Polymer Electrolyte Membrane (PEM) is gaining momentum. Companies are mostly secretive on motivations, but outspoken in marketing. Around, funding is more focused on PEM rather than high-pressure alkaline. One major actor in the field, Hydrogenics, do although state that they sell a modular technology that offer customers any of the technologies of choice. Given low certainty and absence of decision criteria, another concern occur: Is the shift in technological focus related to the lack of success with the former technology? Is it due to certain innovations? Or is it just belief. In between, there is an effort to promote “reverse fuel cells” for hydrogen production, especially, the technology solid oxide fuel cells (SOFC).

In an ongoing project Power-2-Electrolyzer (P2E) the effort has been to create an innovative technological and commercial base for power supply units (PSU) for hydrogen production in hydrolysers. The PSU is technologically somewhat secondary to the hydrolyser, but PSU's has issues that still can justify research especially when upscaling. Issues addressed in the project:

- Galvanic insulation between the power network and the hydrolyser
- Low level of electrical noise on the power network
- Intelligent design for reduced power loss, from 4 % to 1 – 2 %.
- Intelligent use of heat dissipation. Key components are water cooled. The cooling water represent energy that can be utilized for process heating
- The PSU as a demand side resource in the future energy system
- The PSU as a service provider in the energy system for power-factor compensation and frequency regulation
- The PSU and the hydrolyser is expected to spin offs new business services for system aggregators

The project is based on a consortium with the following members:

Member	Background	Motive
Haldor Topsøe A/S (HT)	HT is a Danish company specialized in process chemistry especially catalytic processes. HT has for 15 years worked on development of solide oxide electrolyser cell (SOEC) both can produce hydrogen but also act as fuel cell	HT is interested in PSU systems to ensure innovativeness in power solutions in upscaling of the SOEC technology either to produce hydrogen or electricity
Green Hydrogen A/S (GH)	Is a Danish company from 2009 founded by a number of companies in the energy sector aimed at research and development within high pressure electrolyzers	GH has a focused strategy on megawatt scale electrolyzers and need a PSU well adapted to this purpose
LeanEco A/S (LE)	Is a Danish startup with leading edge technologies in power conversion especially seamless switching between low and high voltage and AC/DC	The developed high-power technology could complement LE's offerings within the power unit industry
Aalborg University, Department of Energy (AAU)	Based on the experience of many years of research in power conversion the P2E project is fitting well within the research profile	To push the limits for effectiveness in PSU from 97 to 99% together with improvements in electrical safety and quality
Aarhus University, Center for Energy	A university research unit with 10 years of experience with field of hydrogen, biogas and commercial and operational issues of energy	To contribute to further commercial aspects of the PSU and hydrogen technology especially reducing heat loss and identify business opportunities

Member	Background	Motive
Technology (CET)		

The P2E project is characteristic for the general effort within hydrogen and fuel cells in its research purpose: To upscale the PSU to megawatt size hydrogen plants and at the same time look deeper into the adjacent areas of potential business model creation based on the technical performance of the PSU and hydrolyzer.

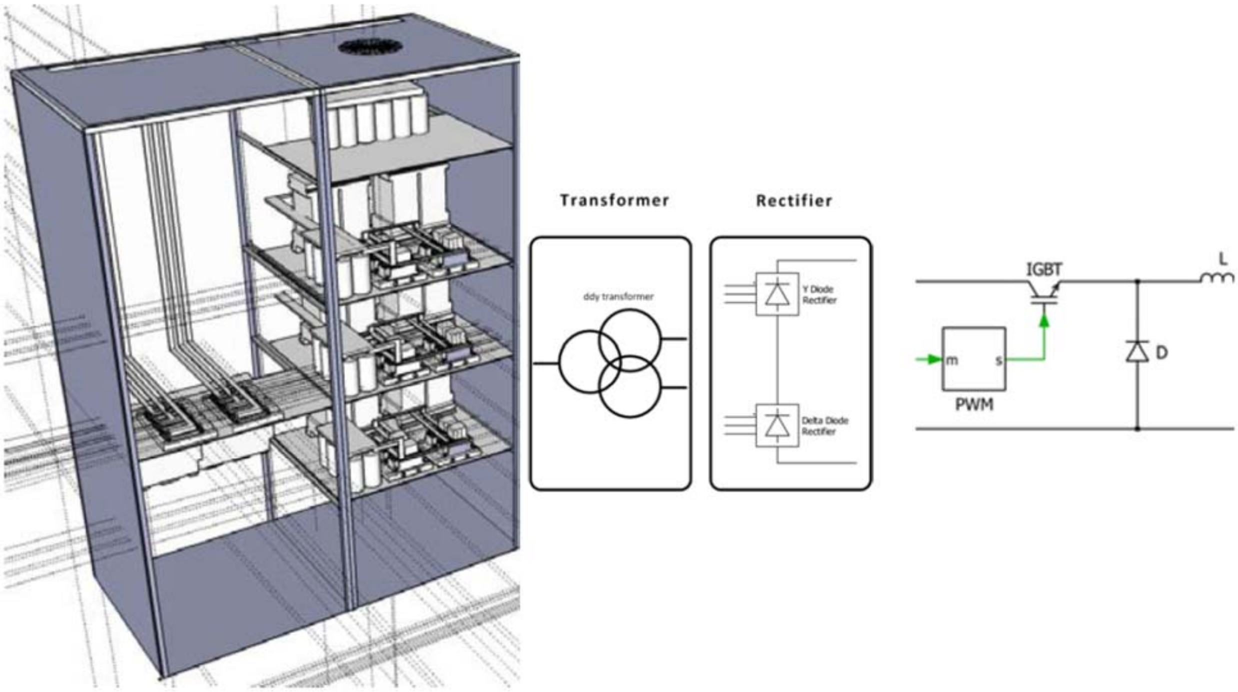

Figure X. PSU cabinet and PSU diagram

With three industrial partners and two universities the project is meeting basic expectations of knowledge creation and intersectorial collaborativeness. However, P2E is one of several projects aiming at bringing hydrogen to the forefront of industrial relevance in form of commercialization and deployment, but the momentum is somewhat failing. GH has during the project stopped commercialization of smaller scale hydrolyzers. LE is struggling to identify VC's and customers. HT has closed its main business units in the area and made the staff redundant, and the two universities have faced dramatic budget reductions also leading to layoffs.

The P2E project is ideal in the immediate assessment frameworks

- Industry – university collaboration
- Knowledge creation
- Knowledge exchange
- Technologies on the forefront of both high power electronics and thermodynamics
- A system integration view placing the technology centrally in the energy transition

- Activities of developing new secondary services in form of quality improvements to the electricity system
- Activities of business modelling

The P2E project is less ideal given the organizational turmoil and reductions of staff at all partners. The identification of actual commercialization opportunities is also not drawing up a clear picture.

DISCUSSION

Clearly, the Danish case of hydrogen and fuel cells is bringing a series of concern on management of technology forth. Management of technology must aim to qualify technologies for deployment or to reject technologies lacking technological, societal, economic or environmental appropriateness. In this case there are elements of:

- Decision making without clear decision parameters.
- Pursuing strategic technologies without a defined or even emergent market
- No relationships to proven technologies
- Prolonged governmental support without actual commercialisation as a result
- No outspoken assessment of the technology as having a high loss of 15 – 25 % per conversion stage

With the case of hydrogen and fuel cells in Denmark, there has been a positive collaboration between risk-willing industrial actors and governmentally backed research and development grants. The line between research and development has not been clear. Research results that have been more or less established as common grounds for development seem to require continuous refinement along development efforts. E.g. the push from kWh to MWh scale hydrolyzers is although relying on completed research creating needs for strong refinements in PSU technologies as well as stronger materials in pipes, valves, membranes and safety measures. Likewise is the absence of proven business models creating a lot of challenges in investigation of “speculative” business model scenarios (Ayers et al., 2012).

Considering OECD’s evaluation approach (OECD, 1997), there is little project-based evaluation as the projects are aggregated into programs and only programs are interacting with policy making. In the case of hydrogen and fuel cells, there seems to miss a timeline issue between the actual program and the OECD guideline given duration of the research in more than 17 years. Also the level selection is problematic in relation to the majority of frameworks that suggest close academia-industry collaboration.

Of the three key assessment motivations

- Energy security
- Knowledge
- Industrial agenda

They are generally recognized as important, but are regarded as incommensurable is research granting and research management processes.

Energy security is ideal but in a research context characterised by numerous competing technologies and solutions. In the current context there are no requirements for describing what future energy scenario that the technology should operate within. This leaves decision makes blindfolded and technology-makers without guiding scenarios that they indicatively substitute with more or less uncoordinated scenarios.

Not at project and not at program level the basic criterias are directly convertible to decision making and there is a fear of contact and discomfort to be outspoken of e.g. research as a distinct part of an industrial agenda. In this sense the research assessment approach of today is somewhat decommercialising research by insisting on that initial commercial success will rule out further funding. Likewise there is a risk in the university – enterprise partnerships that these are asymmetrical in their goals and reward expectations. With a low tradition for commercial involvement of universities, the decommercialised aptitudes of the university might overall contribute to the process of decommercialisation.

RESULTS

The area of hydrogen and fuel cells has had a remarkable history where small scale demonstration efforts, a general media-political hype and evangelists have ensured sustained governmental funds but haven't created production scale systems yet. Given the empirical background a number of issues are indicated: (1) Failure to lock or the strive for the best; no energy technology is ideal but in this area the limits have been pushed and no commercial spin-offs at smaller scale have gotten market momentum. (2) Policy making latency; storage is attractive in high-wind energy systems, but not economically feasible at existing conditions, policy makers could increase storage rewards up to a level of undisputed attraction. (3) "Kill your darlings"; even the newest proposal for priorisation (EUDP, 2014) is basically not priorising anything but is continuously prioritising a lot of technologies. (4) Technologies before business models; the research is predominantly technological and even if there is allocated funds for identifying business models there have not been given funds to actual business model implementations potentially using simpler technologies for simulations. These findings suggest to following augmentation to existing evaluation frameworks:

1. Research must follow trajectories over time that are able to demonstrate commercially mature small scale success
2. Research must be much closer to policy making not only at program level but at actual project level where projects should be able to justify how to cope with political motivations and barriers
3. Research not providing deployable results with a span of years must be fully redefined to ensure credibility
4. Research not adhering to distinct and well defined business models should be considered for the soundness of such
5. Research should be very specific on technological choices, state-of-the-art within the field, and parameterise the remainder; research proposals are mostly more meta-technological and spend much more effort of project governance than technology

This can also be presented as in the figure below:

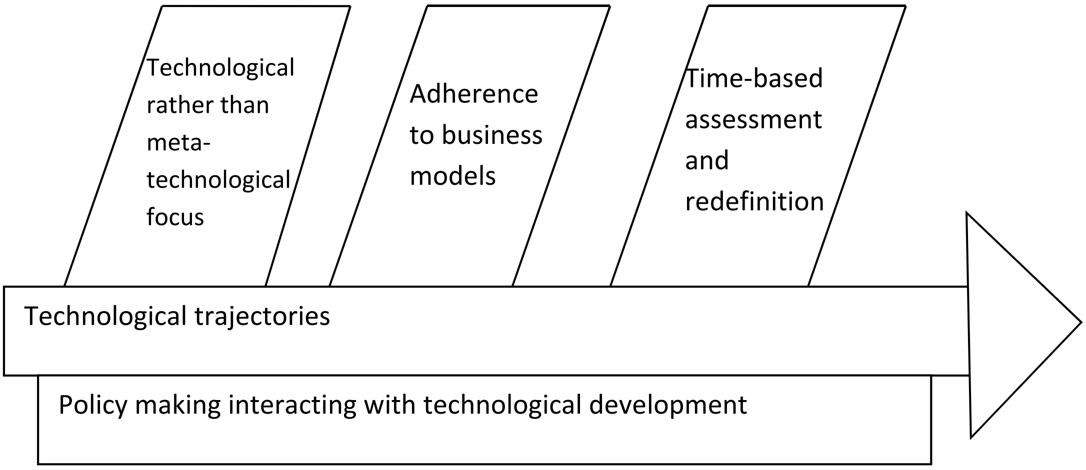

Figure Y. Research decision making augmentation

This is following the overall agenda of energy security, knowledge creation and industrial development but needs to reframe risk. Risk must remain possible, but failure in risk taking should have consequences in assessing and understanding how to navigate better in the research decision making. The paradox is highlighted in Kølsen et al. (2009) where both a higher degree of innovation-risk and improved commercialisation is requested. The process is however complex; the European fusion energy project has been going on since 1970, and has costed billions of EUR without producing energy. Each year the car industry is spending scores of billions on refining the combustion motor that is a 100 year old energy technology. Orrt & Dedehayir (2010) discuss with reference to Hughes that it took more than 30 years to convert the electricity system from DC to AC. The discussed hydrogen and fuel cell initiative has operated in 17 years with petite costs compared to the mega-projects.

CONCLUSION

RES remains critical in the conversion of the energy system, however, decision makers seems to lack guiding principles in the absence of clear dominating, cost-effective and technological reliant principles. Technological extrapolation does not seem to be an option. The area is complex from the competing social, economic and technological frameworks

This paper has limitations in its conclusion related to a Danish context. The Danish context has however during the last decades turned out to be trendsetting to other contexts especially with micro-CHP and WTGs. The papers critique of the existing research assessment frameworks might sound more dystopic than utopic but it is far more a suggestion for reconsidering evaluation of project proposals, project milestones, project outcomes and the relevance and robustness of the governmental research funding reprograms.

This paper has presented a 3-step lens for understanding RES innovation and research: Energy security, knowledge and industrial development. This paper has also presented argument for an absence of dedication to the principles and holding the principles too much in an arms length, when granting funding, so that the agenda will obscure itself. A 5 element plan has furthermore been presented as a consideration for research funding decision makers to augment existing decision making models. Other issues could be brought forth like consortium member symmetry and commercial orientation, but this will open up new discussions of research granting management. Renewable energy is a major priority in many countries and research-based knowledge base is critical for making the right decisions and act as contributor to the global pool of knowledge. Research granting whether governmental, quasi-governmental, venture capitalist or company-internal strategic innovation could prosper from being more specific and more inclusive in augmented models in order to prioritise right among the plenitude of RES and other renewable energy solutions.

REFERENCES

Ajanovic, A. (2008). On the economics of hydrogen from renewable energy sources as an alternative fuel in transport sector in Austria. *International journal of hydrogen energy*, *33*(16), 4223-4234.

Akinyele, D. O., & Rayudu, R. K. (2014). Review of energy storage technologies for sustainable power networks. Sustainable Energy Technologies and Assessments, 8, 74-91.

Ayers, K.E., et al. (2012). Creating a Sustainable Business in the Hydrogen and Fuel Cell Market. Honolulu PRiME 2012, The Electrochemical Society

Balachandra, P., Kristle Nathan, H. S., & Reddy, B. S. (2010). Commercialization of sustainable energy technologies. *Renewable Energy*, *35*(8), 1842-1851.

Bergek, A., Jacobsson, S., & Sandén, B. A. (2008). 'Legitimation'and 'development of positive externalities': two key processes in the formation phase of technological innovation systems. *Technology Analysis & Strategic Management*, *20*(5), 575-592.

Bičáková, O., & Straka, P. (2012). Production of hydrogen from renewable resources and its effectiveness. *International Journal of Hydrogen Energy*, *37*(16), 11563-11578.

Bockris, J. O. M. (2010). Would methanol formed from CO2 from the atmosphere give the advantage of hydrogen at lesser cost? *International Journal of Hydrogen Energy*, *35*(11), 5165-5172.

Boretti, A. (2013). Renewable hydrogen to recycle CO2 to methanol. *International Journal of Hydrogen Energy*, *38*(4), 1806-1812.

Braga, L. B., Silveira, J. L., da Silva, M. E., Tuna, C. E., Machin, E. B., & Pedroso, D. T. (2013). Hydrogen production by biogas steam reforming: A technical, economic and ecological analysis. *Renewable and Sustainable Energy Reviews*, *28*, 166-173.

Brown, J., & Hendry, C. (2009). Public demonstration projects and field trials: Accelerating commercialisation of sustainable technology in solar photovoltaics. *Energy Policy*, *37*(7), 2560-2573.

Buchhorn, A. (2007). Becoming a Market: The Untold Story of Biogas. In *DRUID Winter Conference*.

Bulathsinhala, N. A. (2013). ForskEL and ForskVE - a description, mapping and evaluation of the programmes from 1998-2013. University of Southern Denmark.

Bulathsinhala, N. A. (2014). Ex-ante evaluation of publicly funded R&D projects: Searching for exploration. *Science and Public Policy*, scu035.

Bürer, M. J., & Wüstenhagen, R. (2009). Which renewable energy policy is a venture capitalist's best friend? Empirical evidence from a survey of international cleantech investors. *Energy Policy*, *37*(12), 4997-5006.

Gallego Carrera, D., & Mack, A. (2010). Sustainability assessment of energy technologies via social indicators: Results of a survey among European energy experts. *Energy Policy*, *38*(2), 1030-1039.

Chaurey, A., Krithika, P. R., Palit, D., Rakesh, S., & Sovacool, B. K. (2012). New partnerships and business models for facilitating energy access. *Energy Policy*, *47*, 48-55.

Chiavari, J., & Tam, C. (2011). Good practice policy framework for energy technology research, development and demonstration (RD&D). International Energy Agency, Paris.

Clausen, L. R., Houbak, N., & Elmegaard, B. (2010). Technoeconomic analysis of a methanol plant based on gasification of biomass and electrolysis of water.*Energy*, *35*(5), 2338-2347.

Cleantechnica (2014). 633 Energy Storage Projects Now Underway Worldwide. http://cleantechnica.com/2013/08/10/633-advanced-energy-storage-projects-now-underway-worldwide/

Connolly, D. (2010). *A review of Energy Storage Technologies: For the integration of fluctuating renewable energy*.

Curran, C. S., Bröring, S., & Leker, J. (2010). Anticipating converging industries using publicly available data. *Technological Forecasting and Social Change*, *77*(3), 385-395.

Davis, JM, WJ Kettinger and DG Kuney (2009). When users are IT experts too: the effects of joint IT competence and partnership on satisfaction with enterprise-level systems implementation**.** *Eur. J. of Information Systems*. 18(1).

Delucchi, M. A., & Jacobson, M. Z. (2011). Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies. *Energy Policy*, *39*(3), 1170-1190.

DOE (2005). Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look Forward Committee on Prospective Benefits of DOE's Energy Efficiency and Fossil Energy R&D Programs, National Research Council.

Doucet, G, J Gøtze, P Saha and S Bernard (2009). *Coherency Management – Architecting the Enterprise for Alignment, Agility and Assurance,* AuthorsHouse.

Edler, J., Georghiou, L., Blind, K., & Uyarra, E. (2012). Evaluating the demand side: New challenges for evaluation. *Research Evaluation*, *21*(1), 33-47.

Ekman, C. K., & Jensen, S. H. (2010). Prospects for large scale electricity storage in Denmark. *Energy Conversion and Management*, *51*(6), 1140-1147.

Energistyrelsen (2004) Dansk forskning og udvikling inden for fastoxidbrændselsceller (Danish research and development in solid oxide fuel cells). Copenhagen.

EUDP (2014) Status and recommendations for RD&D on energy storage technologies in a Danish context.Copenhagen.

Gallagher, K.S., et al. (2012) The Energy Technological Innovation System. Annual Review Environmental and Resources. 37, 137–162.

Geels, F. W. (2005). Processes and patterns in transitions and system innovations: refining the co-evolutionary multi-level perspective. *Technological forecasting and social change*, *72*(6), 681-696.

Geovanni, H. G., Orlando, L. D., Rafael, P. D., Alberto, S. J., & Sebastian, P. J. (2010). Analysis of the current methods used to size a wind/hydrogen/fuel cell-integrated system: A new perspective. *International Journal of Energy Research*, *34*(12), 1042-1051.

Grant, D, Hall, R, Wailes, N, Wright, C (2006a). The false promise of technological determinism: the case of enterprise resource planning systems, New Technology, *Work and Employment,* 21:1.

Hansen, A. B., & Nybroe, M. H. (2012, July). Future possibilities—The gas system as flexibility provider for wind power production. In *Power and Energy Society General Meeting, 2012 IEEE* (pp. 1-8). IEEE.

Hemmes, K., Guerrero, J. M., & Zhelev, T. (2012). Highly efficient distributed generation and high-capacity energy storage. *Chemical Engineering and Processing: Process Intensification*, *51*, 18-31.

Hoffman, K. C., & Jorgenson, D. W. (1977). Economic and technological models for evaluation of energy policy. *The Bell Journal of Economics*, 444-466.

Hydrogennet (2014). The Danish Partnership for Hydrogen and Fuel Cells – official homepage. www.hydrogennet.dk

Jacobsson, S., & Bergek, A. (2004). Transforming the energy sector: the evolution of technological systems in renewable energy technology. *Industrial and Corporate Change*, 13(5), 815-849.

Jørgensen, C., & Ropenus, S. (2008). Production price of hydrogen from grid connected electrolysis in a power market with high wind penetration.*International Journal of Hydrogen Energy*, *33*(20), 5335-5344.

Klein, HK and M Myers (1999). A Set of Principles for Conducting and Evaluating Interpretive Field Studies in Information Systems*, MIS Quarterly, 23 (1)*, 67-97.

Kock, N (ed) (2007). Information Systems Action Research – An Applied View on Emerging Concepts and Methods. *Integrated Series on Information Systems 13*.

Konur, O. (2011). The scientometric evaluation of the research on the algae and bio-energy. *Applied Energy*, *88*(10), 3532-3540.

Kølsen, C. et al. (2009). Evaluering af ForskEL programmet 2009. Energinet.dk.

Lee, AS (1989). A Scientific Methodology for MIS Case Studies. *MIS Quarterly,* 13 (1), 33-50.

Loock, M. (2012). Going beyond best technology and lowest price: on renewable energy investors' preference for service-driven business models. *Energy Policy*, *40*, 21-27.

Marbán, G., & Valdés-Solís, T. (2007). Towards the hydrogen economy? *International Journal of Hydrogen Energy*, *32*(12), 1625-1637.

Martin, K. B., & Grasman, S. E. (2006). A feasibility study for hydrogen economy infrastructures. 2006 IIE Annual Conference and Exposition.

Mathiassen, L, and PA Nielsen (2008). Engaged scholarship in IS research, *Scand. J. of Inf. Systems*, 20:2

McDowall, W., & Eames, M. (2006). Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature. *Energy Policy*, *34*(11), 1236-1250.

Muir, L. R., & Williams, D. (1994). Management of R&D program evaluations: A case study of Canada's energy R&D program. *Research Evaluation*, *4*(2), 97-106.

Mulder, G., Hetland, J., & Lenaers, G. (2007). Towards a sustainable hydrogen economy: hydrogen pathways and infrastructure. *International journal of hydrogen energy*, *32*(10), 1324-1331.

OECD (1997). The Evaluation of Scientific Research: Selected Experiences. OECD, Paris.

de Oliveira, W. S., & Fernandes, A. J. (2011). Innovation and Technology Management in Wind Energy Cluster. *Energy and Environment Research*, *1*(1), p175.

Ortt, R., & Dedehayir, O. (2010). Factors hampering technology system progress during the life cycle: What are these factors and how to deal with them?. In *In: Hosni, Y.(ed.). Proceedings of 19th International Conference on Management of Technology, IAMOT 2010, Cairo, Egypt, March, 7-11, 2010*.

Pernick, R., Wilder, C. (2013). Clean Energy Trends 2012. *URL: http://www. cleanedge. com/reports/pdf/Trends2012.pdf*.

Rao, K. U., & Kishore, V. V. N. (2010). A review of technology diffusion models with special reference to renewable energy technologies. *Renewable and Sustainable Energy Reviews*, 14(3), 1070-1078.

Richter, M. (2013). German utilities and distributed PV: How to overcome barriers to business model innovation. *Renewable Energy*, *55*, 456-466.

Richter, M. (2012). Utilities' business models for renewable energy: A review. *Renewable and Sustainable Energy Reviews*, *16*(5), 2483-2493.

Ruegg, R., & Thomas, P. (2009). Tracing government-funded research in wind energy to commercial renewable power generation. *Research Evaluation*, *18*(5), 387-396.

Schilling, M. A. (2010). *Strategic management of technological innovation*. McGraw-Hill

Schoenung, S. (2011). Economic analysis of large-scale hydrogen storage for renewable utility applications. *Sandia National Laboratory, Albuquerque (NM)(2011 Aug) Report No.: SAND20114845. Contract No.: DEAC0494AL85000*.

Schot, J., & Geels, F. W. (2008). Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. *Technology Analysis & Strategic Management*, *20*(5), 537-554.

Schultz M and MJ Hatch (1996). Living with Multiple Paradigms: The Case of a Paradigm Interplay in Organizational Culture Studies, *The Academy of Management Review. 21*, 529-55.

Sovacool, B. K. (2013). An international assessment of energy security performance. *Ecological Economics*, *88*, 148-158.

Sovacool, B. K. (2009). The importance of comprehensiveness in renewable electricity and energy-efficiency policy. *Energy Policy*, *37*(4), 1529-1541.

Stephens, J. C., Wilson, E. J., & Peterson, T. R. (2008). Socio-Political Evaluation of Energy Deployment (SPEED): An integrated research framework analyzing energy technology deployment. *Technological forecasting and social change*, *75*(8), 1224-1246.

Tambo, T. (2011). Smart Grid Innovation Management for SME Electricity Companies. I *Proceedings of the 12. International CINet Conference - Doing more with less.* (s. 987-998). Århus: Continuous Innovation Network (CINet).

Tambo, T. (2012). Utilities' Technology Management of Smart Grid Innovation and Implementation. I C. Mukhopadhyay, K. B. Akhilesh, R. Srinivasan, A. Gurtoo, & P. Ramachandran (red.), *Driving the*

Economy through Innovation and Entrepreneurship: Emerging Agenda for Technology Management . (s. 1-13). Bangalore: Springer.

Tambo, T. and Enevoldsen, P. (2014). Designing Business and Technology Management Work-Packages in Cleantech Research Projects. In *International Management of Technology Annual Conference* (pp. 1-11).

Tidd, J. Bessant, J & Pavitt., K. (2005). *Managing Innovation Integrating Technological, Market and Organizational Change.* John Wiley & Sons.

Tijssen, R. J. (1992). A quantitative assessment of interdisciplinary structures in science and technology: co-classification analysis of energy research.*Research Policy*, *21*(1), 27-44.

Wagner, C. S., & Leydesdorff, L. (2012). An Integrated Impact Indicator: A new definition of 'Impact'with policy relevance'. *Research Evaluation*, rvs012.

Walsham, G (1995). Interpretive case studies in IS research: nature and method, *European Journal of Information Systems*, 4(2): 74-81.

Winkler-Goldstein, R., & Rastetter, A. (2013). Power to Gas: The Final Breakthrough for the Hydrogen Economy?. *Green*, *3*(1), 69-78.

Wüstenhagen, R., & Menichetti, E. (2012). Strategic choices for renewable energy investment: Conceptual framework and opportunities for further research. *Energy Policy*, *40*, 1-10.

Züttel, A., Remhof, A., Borgschulte, A., & Friedrichs, O. (2010). Hydrogen: the future energy carrier. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *368*(1923), 3329-3342.