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Introducing the Theory of Constraints to explore the tidal and marine energy supply chain

Rachel K. Mason-Jones, Paul Davies, and Andrew J. Thomas

Abstract— **This paper presents the importance of understanding supply chain capacity for production and implementation of tidal technologies enabling the sustainable future of the industry sector. The research incorporates identified risks and barriers to explore the renewable technology supply chain from a systems perspective via the Theory of Constraints approach. The methodology enables a holistic supply chain exploration of the Undesirable Effects via a Current Reality Tree diagram. This approach, allows the exploration of the interconnectivity of the holistic supply chain, through a systems thinking approach. Identifying the Undesirable Effects will promote discussion into areas of focus of development needed to enable rapid capacity growth requirements of the tidal energy supply chain. Offering a high-level strategic view of the supply chain ensuring the wider context of the whole system can be examined. The Theory of Constraints approach provides an effective way of understanding the impact a range of factors across the Triple Bottom Line. The paper presents three key areas of focus impacting the tidal industry sector's sustainable future. Firstly, the political aspect shaping policy development and implementation, critical to tidal technologies. Secondly the social dimension which is evident in the identified skills agenda. Finally, that supply chain investment and development is fundamental economic requirement for growth. The detailed mapping of these factors enables the constraints and opportunities within the wider environment to be visible to multiple stakeholders who will shape the future tidal sector.**

Keywords— **Policy, stakeholders, supply chain capacity, Theory of constraints, system mapping.**

I. Introduction

MANY governments are expected to meet renewable usage targets within their energy mix in 2020 and beyond (notably 2050). Therefore it is important to understand not only the current and projected renewable energy generation capability but also to understand the renewable technology production supply chain capacity to manufacture and implement the renewable technologies out in the field both now and in the future. This paper presents research undertaken to explore the perceptions of risks and barriers that can inhibit the capacity growth required to develop the renewable energy sector supply chain and analyses them from a systems thinking perspective. The research focused on understanding and analysing the renewable technology supply chain (with a focus on tidal and marine) within Wales, UK. We present the potential value of taking a Theory of Constraints (ToC) approach to understanding the sector's interconnectivity of the risks and barriers and to explore the key Undesirable Effects (UDE) of the system via a Current Reality Tree (CRT). This will enable informed supply chain strategy development via removal or minimisation of the UDE's within the system. Thereby enabling the tidal technology supply chain to rapidly increase its capacity to allow renewable energy to play a central role in energy security in the medium to long term. The paper is structured in the following way. The first section sets the context for the need for renewable energy sector growth and the capacity pressure this entails. The literature review then establishes key ideas around risks and barriers within supply chain theory alongside the establishment of the TOC concept. The methodology section presents the research that forms the basis of this paper and this is followed by the Discussion of the key themes that emerge from the data. Finally, the Conclusion draws the main aspects of the paper together and presents consideration of how the research can be developed into the future.

With the UK having committed to an 80% reduction in greenhouse gases by 2050 [1] and a short term target of 15% of energy requirements coming from renewable technology by 2020 [2] there is much discussion about whether the targets will be achieved [1, 3]. Meeting these targets will obviously require renewable generating technology to be both available and operating [1]. This requirement has therefore put the spotlight on the need to

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R.K. Mason-Jones is with the Value Stream Research Group, Cardiff Metropolitan University, Llandaff Campus, Western Avenue Cardiff, CF5 2YB UK. (e-mail: rkmason-jones@cardiffmet.ac.uk).

P. Davies is at, University of South Wales, Pontypridd, UK, CF37 1DL UK. (e-mail: pdavies1@southwalest.ac.uk).

A.J. Thomas is at, Cardiff Metropolitan University, Llandaff Campus, Western Avenue Cardiff, CF5 2YB UK. (e-mail: ajthomas@cardiffmet.ac.uk).

develop sufficient supply chain capacity to produce and implement the needed renewable technologies to get them fully operational within a relatively short time. In order to enable the development of sufficient capacity requires growth that is not just incumbent on companies currently engaged in the renewable energy supply chain but also expansion into companies who have not traditionally engaged with the renewable sector supply. Thus, the commitment to a renewable strand to energy supply presents a potential business opportunity to companies across a range of specialisms. Yet, the decision of a business to diversify into the renewable sector is not necessarily a straightforward consideration. The existence of barriers and risks, both real and perceived, to such a venture are inherent factors to consider. Inevitably, the view of companies is essential in articulating the varied obstacles to enabling the capacity growth required by the sector. To help articulate this perspective the paper draws together data from a survey conducted across companies in Wales, UK that explored the perception of risks and barriers associated with engaging with the renewable technology sector. This information has been used to develop and articulate a holistic systems view, via the ToC approach, of the renewable technology supply chain and its capability to rapidly increase its capacity to produce and install the needed equipment to meet the 2020 and beyond energy targets. The research has used the CRT approach within ToC to explore how the interconnectivity of the risks and barriers effects the system and hence allows the identification of the key UDEs that need to be focused on to optimise the supply chain.

II. Literature Review

Strategic growth inevitably necessitates change with the degree of certainty involved being variable [4]. This is particularly the case where the change involves diversification of product or market as the development of capacity within the renewable energy sector would appear to require [5]. Invariably, there are risks and barriers that will be integral to the way that the strategic direction is realised [6] However, it would be misleading to consider the two terms to be one and the same, though inevitably they are related. Each has particular aspects that determine the way that they are likely to impact on a business and this study considers them as distinct elements informing the way companies perceive the economic attractiveness of the renewable sector.

Risks are an inherent part of business activity as resources are invested to achieve the desired future direction with a clear awareness that uncertainties exist. Barriers differ in that they are more concerned with existing external factors that may impact on the business. Invariably, the existence of barriers plays an important part in evaluating the risk to the business but they need to be understood in their own right [6]. The ability to minimise or even remove potential barriers can make a major difference to the initial decision to undertake the chosen direction as well as the way in which the change is enacted [7]. Inevitably, there are common types of barriers that exist across most business environments and it is the way that they are impacting the particular context that becomes the main focus of attention.

The issue of risk and barriers within the renewable sector were identified by DECC [1] the report stated that there is a need to remove the supply chain barriers to enable the UK to meet provide the needed capacity for the 2020 targets and beyond. The research for this paper has utilised the idea of risks and barriers and linked them to the understanding of the constraints within a supply chain to enable a detailed examination of the holistic renewable supply chain with focus on the marine and tidal technologies. Risks are defined as "uncertain events" that have an impact on performance and may have an undesirable outcomes [8, 9]. Whereas barriers in supply chain management can be seen as blockages that need identifying and removing or easing in order to improve performance, with the first step being the need to identify the barriers [10]. Goldratt [11] defines a constraint as a bottleneck, which governs the output of a system or process. Therefore the identified and understood risks and barriers within the renewable supply chain inform our understanding of the potential constraints of the system. This paper presents the outcome of a survey examining an understanding and ranking of a series of identified risks and barriers within the renewable sector supply chain and uses this to inform and develop a Theory of Constraints (ToC) diagram as a vehicle to understanding in terms of the holistic supply chain as the system under scrutiny. By understanding the system as a whole and being able to examine and understand the risks and barriers that represent the constraints to the system we are able to facilitate discussions that can develop solutions and offer an opportunity to improve the supply chain performance, [12]. As stated by Caniels and Romijn [13] "innovation is not merely a matter of designing new products or improved processes within the boundaries of a single firm, but involves re-organisation and adjustment of entire chains. In some cases completely new chains may even need to come into existence"

Understanding of the potential risks and barriers that a supply chain may be subjected to, enables proactive strategies to be developed that allows the supply chain to either avoid the potential risk or if that is not possible to ensure the risk itself can be adequately management to minimise its impact on the supply chain performance both now and in the future, [14,15,12]. Walters [16] stated the first step is to acknowledge there are risks in the supply chain that need to be managed. DECC [1,3] identify the need to understand the supply chain barriers within the renewable sector to enable development and successful implementation of needed projects to meet the renewable energy targets. This focus on solution development is echoed by Fawcett et al [17] who discuss that rather than

viewing barriers as stand alone issues that need to be targeted and removed, barrier identification should be undertaken holistically thereby ensuring solutions (termed bridges) can be adequately developed and implemented. Thus a detailed understanding of the holistic supply chains potential risks and barriers is crucial to enable a full understanding of the forces effecting the system as a whole.

From preceding research undertaken, it was shown that in order to explore the challenges ahead in the renewable sector more detailed understanding of the potential risks and barriers faced was required, [18]. To fully explore opportunities for potential capacity growth of the renewable technology supply chain to meet the needed energy targets there is a need to examine the perceived risks and barriers that may impede engagement and development within the sector.

A detailed understanding of the holistic supply chains potential risks and barriers is crucial to enable a full understanding of the forces effecting the system as a whole. Taking a holistic overview also ensures effective supply chain wide strategic approaches are established to ease and potentially eradicate the risks and barriers identified. This holistic view is particularly useful when considering the renewable sector and its needed developed because in order to ensure there is sufficient and growing capacity we need to understand the holistic supply chain and the potential gaps in both capacity and expertise. Ackoff [19] highlighted that a system is essentially a "product of its interactions" [20]. Hence the systems view will offer an understanding of the interconnectivity and relationships within the supply chain that will inform detailed discussions on how to enable focused strategic development where most needed to enhance the capacity development for future requirements. The holistic nature of systems thinking should enable a more informed understanding surrounding dynamic decision making by ensuring the form of communication and language used is visual and diagrammatic by translating perceptions into explicit pictures highlighting the key risks and barriers as a result of interaction between players in the system. This approach enables both a useful communication tool to present the perceptions and their interconnectivity but also enhances and informs discussions when exploring future developments and improvements. One particularly useful approach is a casual loop diagram which enables development of a big picture view [20] which explores the interrelationships within the system and for our research the renewable supply chain. In this research we utilised the Theory of Constraints (ToC) Critical Reality Tree (CRT) approach. In order to utilise the ToC approach we focused on risks as potential constraints and barriers as established constraints within the system (in this case the renewable supply chain).

The Theory of Constraints is a useful approach when considering the potential bottlenecks (constraints) to the performance of a system and/or process [11]. It enables and encourages the system under consideration to be examined holistically with a view that you need to understand the whole to fully understand the impact of the constraints, examining small sections of a process or system may mean the true constraint is missed, [21]. Within the ToC literature Goldratt [11] defined a constraint as a bottleneck that governs a processes output. With Goldratt and Cox [21] defining a constraint as something that impedes the system from achieving its goal therefore effective action has to be taken to remove or reduce the constraints to enable improvement in the holistic system, [22]. Therefore identifying your constraints and eliminating them will enable significant performance improvement. There is a temptation to consider the Theory of Constraints as a primarily process focused approach however as outlined by Thomas et al [23] it can be considered wider than a individual component or process but rather as focused on the whole system, thereby endorsing its usage as a holistic supply chain approach. Although traditionally the ToC approach has been applied to single organisations as a primarily operations management technique, there is evidence of ToC being applied within the supply chain perspective [24]. The interesting point made by Thomas et al [23] is the mention of a system, in much ToC literature and case studies the system tends to be viewed as an individual organisation, albeit with influences coming in from the external environment. However within this research the ToC theory was applied across the renewable supply chain as a whole, thereby the system in this case was viewed as the holistic supply chain rather than an individual company. This view of the system is in line with the concept of the extended enterprise [25]. The extended enterprise perspective aligns well with view of Goldratt [11], and Dettmer [26] who explore the idea that system under consideration in ToC can be a chain composed of many links, or networks of chains thereby suggesting its appropriate application and usage within supply chain management. This system perspective is further highlighted by Bowersox et at [27] when they estimated only about 20 percent of potential improvement initiatives are within the responsibility of an individual organisation, whereas 80% involves responsibility of other parties [24]. Simatupang et al [24] further emphasis the importance of considering the wider connected system when utilising ToC when they stated that the constraint based approach to performance improvement needs to recognise the importance of identifying the constraints that prevents the supply chain and its members from achieving the necessary performance requirements, hence again reiterating the wider holistic system approach. The renewable supply chain is seen to currently have a variety of constraints that need to be both identified and understood in detail associated with development and capacity expansion especially given the short time scales

needed to meet the 2020 target of 15% of energy sourced from renewables as well as the later 2050 targets [1].

The use of ToC in a supply chain system has gained acceptance [28] and can be seen to have been used as an appropriate management tool to explore and manage potential supply chain improvements [29, 30]. Oglethrope and Heron [31] utilised the TOC as an approach to explore the potential barriers within the UK food supply chain outlining that "theory of constraints (ToC), as a potential means by which businesses can manage and navigate those barriers". Our research is focused on identifying and understanding the perceived risks and barriers to the renewable supply chain both now and for future development. By viewing these risk and barriers as constraints for capacity growth within the supply chain it enables us to explore these perceptions via a ToC lens on the system as a whole identifying any bottlenecks (constraints) that would limit a sector from achieving its targets [11]. The ToC approach not only offers a recognised systematic approach for exploring the renewable supply chain's current growth constraints but also offers a useful visual communication tool to examine and discuss future strategic decision making to remove the barriers to future growth potential. Within the ToC approach is the Current Reality Tree (CRT) diagram. The CRT diagram will enable the current As-Is to be presented, therefore allowing discussion to develop on which constraints need to be tackled. The advantage of the CRT is it enables the development of a diagram that succinctly presents a problem scenario utilising the understanding of the perceived issues within a system. It explores the issue via a cause and effect approach allowing identification and understanding of the interconnectivity of risks and barriers which are the system constraints.

III. METHODOLOGY

The research was split into distinct three phases as we moved through the identification and exploration of the risks and barriers to the renewable supply chain, this enabled us to ensure a systematic coherent approach [32]. Phase one was to identify a set of risks and barriers recognised as affecting the renewable supply chain, this was undertaken via secondary data research, a series of interviews and roundtable discussions. Phase two explored the identified risks and barriers with the wider industrial community via a survey to both explore if companies recognised them as potential issues and also undertake a ranking exercise of perceived importance. Phase three of the research utilised the information gathered from phase one and two to develop a CRT diagram to both illustrate the interconnectedness of the risks and barriers within the renewable supply chain system and to identify the key UDEs.

In order to explore the perceptions of risks and barriers in the renewable sector supply chain the Phase One of the research was to identify an agreed set of them. The process undertaken to produce a testable set of risks and barriers was to conduct analysis of secondary data, a series of round table discussions and interviews. The secondary data was obtained via the undertaking of a literature search focused on risks and barriers within the supply chain management field. Utilising a roundtable discussion is a useful approach to exploring group opinion with a variety of stakeholders thereby offering an informed starting point [33, 32]. The roundtable discussions included contributions from individuals representing the Welsh Government, key renewable technology companies and industry sector bodies. The engagement of these stakeholders ensured a cross section of views and opinions, encapsulating the perceptions of risks and barriers informing the study. Within these meetings the attendees were asked what risks and barriers they felt were currently impacting the renewable sector supply chain. We also undertook a series of semi structured interviews with companies in the renewable sector and industry bodies to discuss in detail what they felt the risks and barriers were, this enabled us to determine a more detailed and nuanced viewpoint from within the industry sector [34, 32]. This triangulation approach enabled a coherent and agreed set of risk and barriers to be explored in the research.

During Phase Two the identified risks and barriers were then tested primarily via a survey to see if they were recognised by industry [35] and also to ask respondents to rank them by importance. The data used in this paper is taken from a survey sent out to Welsh companies and was run in conjunction with the South Wales Chamber of Commerce and utilised a number of industry and government avenues to maximise the response rate. In total 297 companies completed the survey, conducted through SurveyMonkey. The survey was available electronically to enable ease of access and to make completion as straightforward as possible [36]. The response rate has enabled a good overview of opinions to be explored and covered a number of specialisms including manufacturing, technology development, consultancy, engineering, installation and support & composites [37]. Importantly for the research, the companies encompassed three levels of engagement with the renewable sector; those regularly involved; those with intermittent activity; those not engaged in any way [38]. The segments ensured the research has been conducted to capture views and opinions not only of companies within the renewable technology supply chains but also from companies who have yet to work within the sector. It was felt important to elicit views from those companies not engaged in the renewable sector so we could explore perceptions of risks and barriers from companies who could potential engage in the future and therefore enhance the potential overall capacity of the supply chain. Questions were structured with varying options for response. In some instances responses were simply levels of agreement to determine the strength of feeling across the companies sampled. For other questions there were

several options that could be selected, as the intention was to determine the level of perception across a range of risks and barriers. If the respondents were simply asked to select the most important option this could ignore other, only slightly less considered factors [39]. As the paper is concerned with the views of companies in a more holistic manner it was understood that the deeper response offered by multiple answers provides a greater representation of the risks and barriers that exist in relation to realising renewable energy opportunities.

Phase Three of the research utilised the findings from the survey, roundtable discussions and interviews to develop a CRT. The survey was undertaken to explore the issues surrounding potential capacity constraints surrounding the needed capacity growth in the renewable supply chain. The examination and ranking of the identified risks and barriers for the sector were therefore seen as the constraints surrounding this potential growth. Thus, by visualising the risks and barriers as the constraints of the supply chain a link to the Theory of Constraints was enabled. The produced list of risks and barriers are useful to our understanding of importance within the supply chain but alone it could be argued offer a linear understanding, however, by utilising our understanding of them to inform and develop a ToC CRT diagram we are exploring an understanding of their influence and interconnectivity within the system structure. The CRT approach offers a useful methodology to explore the current system status and inform discussions on how to develop the system to remove or reduce the impact of constraints both known and initially hidden [28]. Therefore enabling a design thinking approach to the renewable supply chain through the advantage of looking at the problem as an extended enterprise holistic system. As stated by Banerjee and Mukhopadhyay [28] "In ToC parlance the design thinking can help discover hidden constraints of a business problem and help design a solution which is technologically feasible and strategically viable to overcome constraints". Hence, from the ranking exercise achieved by the survey combined with the interviews and roundtable discussions an understanding of importance of each risk and barrier in relation to each other and the overall view of the respondents was used to develop the ToC CRT diagram. This enabled us to explore how the perceived risks and barriers are connected and therefore examine how the hard and soft indicators within cause and effect are identified [40]. Thereby allowing a system view of the constraints surrounding the renewable supply chain as whole to be developed. In order to explore the validity of the constructed CRT diagram a meeting was held with industry experts within the renewable sector where the diagram was presented and discussed to facilitate feedback and comments to be collated on the specific components of the diagram. This enabled discussions to explore whether the diagram did offer a realistic representation of the renewable sector as understood by the industry sector itself and hence can inform supply chain strategic decision making in the future.

IV. Discussion

Phase one of the research focused on the identification of key risks and barriers to growth in the marine and tidal renewable technology supply chain. From the secondary desk research, and primary data round table meetings and interviews, nine risks and five barriers were identified, illustrated in Table I below. In order to satisfy the relevance of the identified factors the list of risks and barriers was presented to a further roundtable discussion to gain agreement that these were recognised and felt to be the key issues, therefore the set shown in Table I were taken forward to Phase Two of the research.

TABLE I
RENEWABLE SUPPLY CHAIN RISKS AND BARRIERS

Risks	Barriers
Planning Issues	Red tape & planning constraints
Distraction from Core Business	Ability to connect supply chain members
Competitive	Presence of large international companies
No long-term opportunity	Adaptation of expertise
Capacity constraints	Readiness of business to respond
Uncertainty development	
Lack of knowledge of the sector	
Financial investment	
One of projects; lack of continuity	

Phase two of the research involved analysing the results of the survey. The survey participants included companies currently engaged within the renewable technologies supply chains and those that weren't. This was considered important due to the previously stated point that in order to enable rapid capacity growth the sector needs both existing companies in the renewable supply chain plus new industry entrants via companies diversifying business into the renewable sector. Figure 1 presents the responses to the survey showed that the companies both recognised the risks and also that some risks were seen as significantly more important than others.

Significant amongst the risks is the degree of uncertainty that planned projects will be fully realised and actually see the light of day. This risk is coupled with the perception that projects are one-offs and thus do not offer a continuity of business it is evident that a significant fear over the sustainability of the business opportunity is felt by many of the respondents.

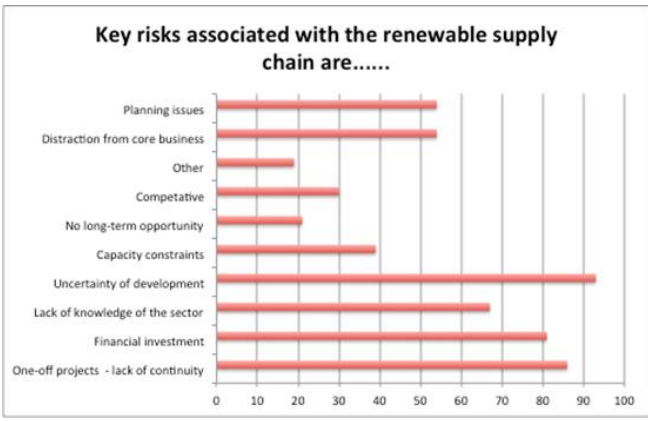


Fig. 2. Risk analysis survey results.

Particularly where companies are considering diversifying away from the established areas of the business it can be seen that this encompasses a significant risk for the business to consider, one that may prove too strong to ignore. Many of the respondents ranked the risk surrounding a lack of knowledge of the sector quite highly. Clearly, the opportunity of economic gain is undermined by the perceived lack of sustainability and undermines any strategic benefit that the sector may have held. The lack of knowledge of the renewable sector would seem to compound these concerns and may be a reason for the high response to the risks. However, the lack of long-term opportunity is the least recognised risk from the respondents indicating that the uncertainty of development and one-off projects are not a given, but a concern that this is how the sector may develop. Thus, there is a signal for those shaping the sector to understand the 'mood music' that needs to be projected and the way that growth opportunities are communicated to a wider business audience and indeed being seen to address the key perceived risks.

The survey also asked participants about their perceptions of the previously identified key barriers within the renewable technology supply chain.

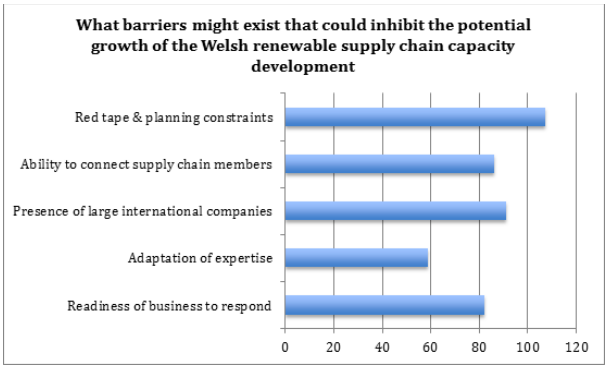


Fig. 3. Barriers analysis survey results.

Reinforcing the risk of uncertainty, evident from Figure 1, the most recognised barrier relates to red tape and planning constraints. It is perhaps of concern that a significant barrier to growth is perceived as an external one as this is less within the scope of the sector to address. A requirement to engage and inform government bodies is implied in this barrier and is inevitably a more hazardous undertaking; yet one that is necessary. The remaining barriers are more clearly in the realm of the renewable sector and businesses interested in engaging the supply chain.

Two responses jump out from Figure 3 and are related to each other. The lack of awareness and knowledge of opportunities are significant barriers to engagement of companies as they inevitably kill potential ambition at source. If the potential opportunities are not registered then they cannot be explored. The onus here is on the main players within the sector to more effectively communicate the economic opportunity, particularly to those companies that are not already engaged and thus are outside the community. In order to achieve the required capacity growth to meet renewable targets it is imperative that the focus of activity is not simply preaching to the converted. There are new members of the congregation wanting to be invited in but not sure who they should be asking.

The ranking exercise undertaken as part of the conducted survey enabled us to highlight the key risks and barriers from the perception of industry. This information was utilised in Phase three to develop a ToC CRT diagram which would enable the renewable supply chain system to be represented, communicated and discussed. The survey results surrounding the perception of the risks and barriers coupled with the interviews and round table discussions suggested three key area's of potential constraints: supply chain, policy and investments and finally skills. Therefore as a starting point the CRT diagram was set up to visually represent these three key areas and their linkages within the renewable sector. The original question that was established at the initiation of this research was used as the central consideration in the development of the CRT system diagram. This overarching concern for the system is "Welsh supply chain companies are not orientated towards developing renewable energy technologies". The CRT utilises a cause and effect logic approach, this allowed the research to explore discourse surrounding the challenges and factors and therefore investigate UDEs. In terms of supply chain capacity growth, especially the potential need for rapid capacity growth, readiness of the supply chain to respond was seen as key.

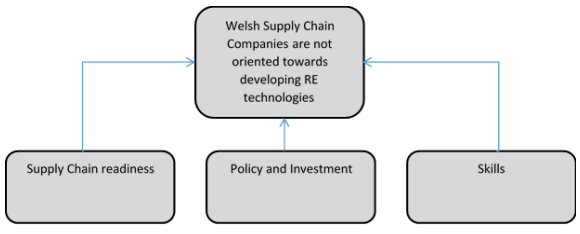


Fig. 4. Three key sections of Current Reality Tree.

CRT diagrams were then developed for the three identified areas as shown in Figure 4, which led to a detailed representation of the interconnectivity of the issues and discussed factors with the stakeholders. Given the limitations of space within the paper format the complete CRT diagram cannot be shown, however to give a flavour the detailed diagram of the Supply Chain Readiness section from Figure 4 is shown in the Appendix. As previously stated the goal is to understand the interconnectivity and relational factors to highlight potential bottlenecks and hence open discussion surrounding the UDE's of the system under examination [28]. By focusing on the key UDEs the system can then focus its attention on resolving or minimizing their effect to improve the performance [22]. The construction of the CRT high level diagram outlined 45 separate factors associated with exploring the overall statement 'Welsh supply chain companies are not orientated towards developing Renewable Technologies'. In order to identify the key (most potentially problematic) UDEs of the system the CRT diagrams were examined and the factors with the majority of interconnectivity links were highlighted. From this, analysis of the diagrams allowed an identification of six key UDEs shown in Table II. Therefore to improve the capability of the system (in this case the supply chain) to maximise opportunity to increase capacity there is a need to focus on the key 6 UDEs.

TABLE II
SIX KEY UDES IDENTIFIED

Main area of focus	Key UDEs identified
Supply Chain Readiness	1. Companies need a clear strategic direction to identify specific technologies to develop 2. Companies do not have the resources to support new technologies'
Policy and Investment	3. Investment in Renewable Technologies currently focused on service/maintenance and high value manufacturing opportunities are being lost 4. Need for a clear strategic development programme is needed from Welsh Government in order to align companies and lead the way 5. Welsh supply chain companies readiness to respond is poor. Need to focus on Technology Readiness Levels development
Skills	6. Company readiness levels are limited and not fit for current demands

In order to explore UDEs and outline the ToC constraints in the system the research then assessed each UDE in terms of the risks and barriers used to drive the investigation (outlined in Table I). From the perspective of Supply Chain Readiness the two key UDEs identified brought to the forefront risks surrounding 'uncertainty development' and 'lack of continuity' and the barrier surrounding the 'adaptation of expertise'. Under the Policy and Investment section of the diagram there is a focus surrounding the risks 'Competitiveness', 'lack of knowledge of the sector' issues and primarily connected to the barriers such as ability of to 'connect to supply chain members' and 'the readiness to respond' factors. In the Skills section of the CRT one key UDE was highlighted and is found to be particularly focused on risks such as 'uncertainty development' and 'lack of knowledge of the sector' and is a direct result of barriers such as 'adaption of expertise' and 'readiness of business to respond.'

The analysis of the key UDEs highlights the urgent need for policy development and intervention to promote the needed environment for sector development and strategic direction guidance, this finding aligns well with the policy risk analysis conducted by Gatzert and Kosub, [44]. What also becomes clear when focusing in on the 6 key UDEs and their contributing risks and barriers is the needed focus on skills development both within specific renewable technology areas but also in supply chain knowledge and development. This has the added advantage of increasing and developing knowledge and opportunities for innovation and performance improvement as the recognised supply chain system and collaborative relationship density increases, [41]. Which can additionally have a potentially positive impact on supply chain performance, readiness and competitiveness opportunities, [42]. Interestingly skills development and in this research a barrier surrounding adaption of expertise is ranked quite highly which aligns with Painuly, [43] indicating this is still an issue 18 years on.

The identification the key UDEs and their associated risks and barriers although interesting is only step one. Detailed cause and effect analysis is needed to fully explore the root causes, [45, 26]. This will then allow research into and the construction of a Future Reality Tree (FRT) and therefore enable detailed discussion around moving from the CRT to the FRT, [45, 26].

V. CONCLUSION

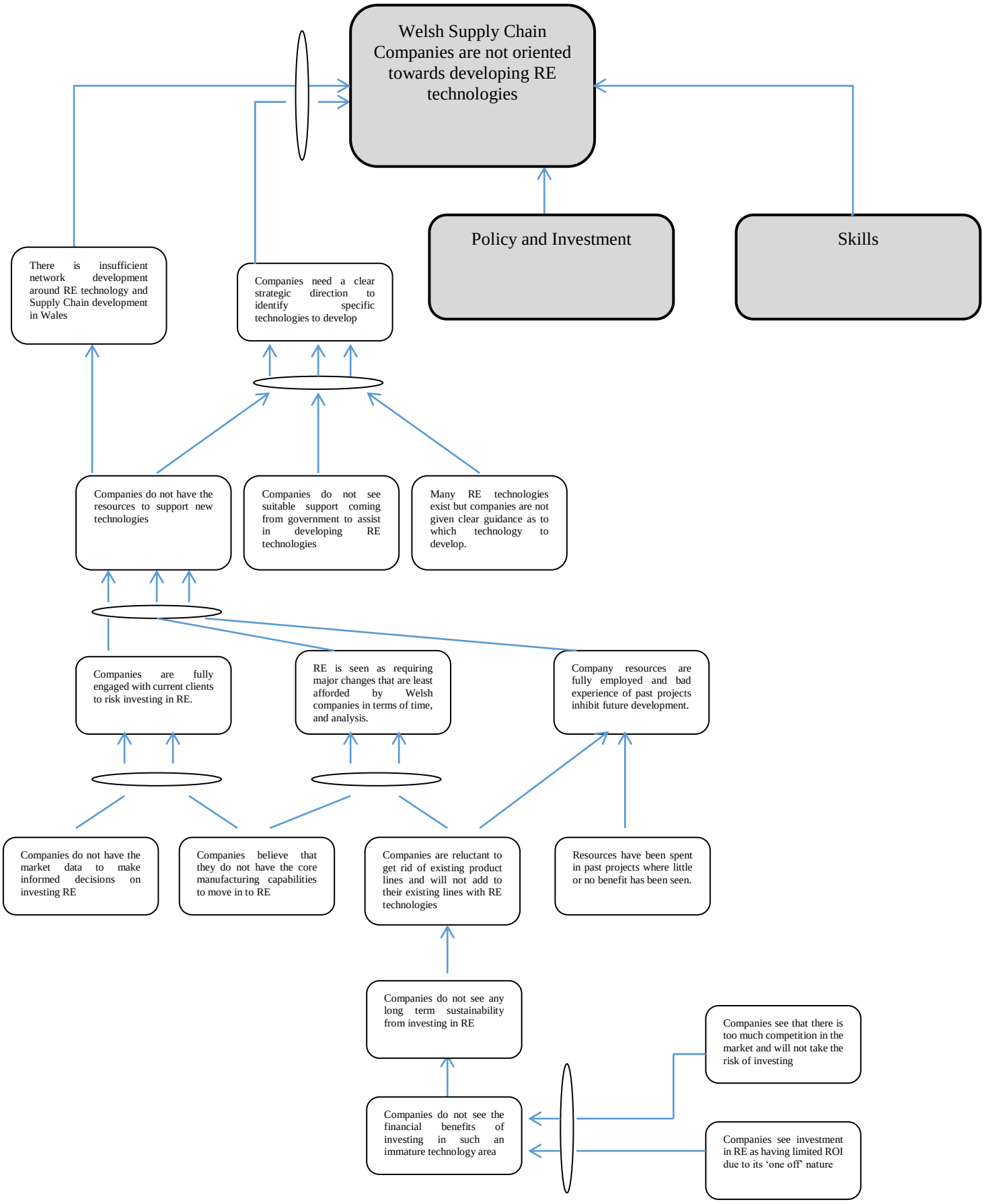
The ToC CRT process allowed the research to take a holistic view of the renewable technology supply chain with a view to exploring the implications and challenges of rapid capacity growth needed to supply sufficient technology in the field to meet renewable energy usage targets over the next 30 years. Analysing a supply chain as a whole can be highly complex however taking this high-level system view allowed a snapshot of the key issues from the strategic level. Utilising the CRT approach to analyse the system indicated 6 key UDE's to focus on to enable capacity growth within the sector, Thereby highlighting the need for a multifaceted approach to developing the capacity in the renewable technology supply chain. It cannot be left to individual companies to make the necessary changes, a systems approach taking into account development of the holistic supply chain as well as policy level intervention is required. What is clear when analysing the holistic system is that this multifaceted approach will be needed in order to enable capacity growth in the renewable technology supply chain to occur in a sustainable fashion to ensure resilient industry sector for the future.

APPENDIX

Included in this appendix is the more detailed 'Supply chain readiness' section of the constructed CRT diagram

referred to within the discussion section of the paper. Due to space constraints the detailed 'Policy and Investment' and 'Skills' sections of the CRT are not shown.

Supply Chain Readiness section of the CRT diagram.



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