Toward Sociotechnical Transition Technology Roadmaps: A Proposed Framework for Large-Scale Projects in Developing Countries

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***Abstract*—Governments and industries continuously engage in large-scale projects aiming to unlock economic potential for commercial and social benefits of a country and its people. In the case of developing countries, where the dynamics of innovation ecosystems differ from those in developed countries, the need for sociotechnical transition projects are often quite high. The aim of this article is to propose a standardized framework suitable for developing countries for the technology roadmapping of large projects aimed to bring about systemic sociotechnical transitions. The framework is developed through the integration of existing generic technology roadmapping approaches with transition management theory and complex systems theory and was illustrated against a successful sociotechnical transition program that is characterized by Big Fast Results (BFR) requirements. Data were collected from qualitative interviews as well as from the critical analysis of relevant documents. The proposed sociotechnical transition technology roadmap accurately captured the key elements of the BFR project it was benchmarked against and even identified key elements that were not included in the BFR methodology. An advantage of the proposed sociotechnical transition technology framework is the fact that it makes use of a standard technology roadmapping process with few customizations that are ideal for use in developing countries.**

***Index Terms*—Complex systems, developing countries, large scale projects, sociotechnical transitions, technology roadmaps.**

I. Introduction

SINCE the introduction of the technology roadmapping process by Motorola as a technology analysis and planning tool [1], there has been considerable interest in the theory and practice of its usage, its development process, customization according to various management needs, integration with the organizations' strategic and operational processes and integration with other technology planning tools. Technology roadmapping evolved from a simple process that focused on the incorporation of technology in corporate planning processes [2] to a more robust process in managing complex innovation systems. Fourth industrial revolution technology systems, entailing the convergence of cyber-physical systems as examples of such complex systems, recently placed technology roadmaps in the spotlight as organizations, industries, and countries prepare for this important transition.

What makes technology roadmaps even more appealing in this era of change is the fact that they provide a concrete pathway in linking future market and societal needs with the complex products, systems and services that are necessary for sociotechnical transitions. Sociotechnical transitions are described as the development or introduction of new technologies leading to new socio-technical configurations [3]. Sociotechnical transitions take into account the complex and multifaceted nature of transitions (also called system innovations) which not only requires the development and use of new technologies, but also involves changes in user practices, policy and regulation, infrastructure, networks, and institutions [4].

National Governments continuously engage in large-scale projects that aim to unlock economic potential for commercial and social benefits of the country and its people. These projects are typically executed in innovation ecosystems that are characterized by complexity due to the interactions between role players in government, industry, and research organizations and are therefore good examples of systemic sociotechnical transitions. Although there is a wider interest in theory and application of sociotechnical transition in developed countries, this article focuses on its application for technology roadmapping in developing countries. We argue that in the case of developing countries, the need for sociotechnical transitions is often quite high. In this article, developing countries refer to middle to low-income countries whose gross national income per capita does not exceed $12 535, as classified by The World Bank for 2021 fiscal year. The dynamics of innovation ecosystems in developing countries differ from those in developed countries due to aspects such as a lack of sufficient technology base and science and technology human capital, making technology planning more difficult [5]. Existing roadmapping methods for products and emerging technologies are more suitable where an established technological capability within the surrounding ecosystem is already present. This highlights the need for a standardized framework for the technology roadmapping of sociotechnical transitions in large-scale projects in developing countries and defines the research gap on which this article was based.

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The aim of this article is to propose an appropriate framework suitable for developing countries for roadmapping of large projects aimed to bring about systemic sociotechnical transitions that influence a broad range of stakeholders (i.e., government, industry, and research organizations), horizontally and vertically. The research was conducted in the background of the Big Fast Results (BFR) methodology developed and implemented by the Malaysian government as a framework for their sociotechnical transition projects that was executed with great success [6].

The BFR methodology is "a holistic and granular transformation approach designed to deliver a specific goal within a stipulated period of time" and focuses on bringing stakeholders from the public, private, and academic sectors together in the analysis, planning, and delivery of large projects [7]. We will show that the seven steps of the BFR methodology can be superimposed on the three phases of technology roadmap development, namely preliminary activities, technology roadmap development, and follow-up activities. The electronics and electrical (E&E) sector roadmap of Malaysia, developed through the use of the BFR methodology, is therefore used as a case to illustrate the proposed framework as a standard framework for technology roadmapping of sociotechnical transitions in developing countries. A detailed discussion and analysis of the Malaysian BFR approach follows in Section V.

This article is therefore useful to the National Governments and technology roadmapping practitioners in developing countries for the development of technology roadmaps with the objective of achieving transformational delivery outcomes that brings about new economic, technological, and social developments within a short-period of time. Complex systemic challenges in developing countries make it difficult to develop technology roadmaps that are feasible, resourced, and well-coordinated. Section III discusses in detail on the concepts of socio-technical transitions and technological leapfrogging. A theoretical contribution relates to the integration of the technology roadmapping framework with other technology management knowledge domains.

The rest of this article is organized as follows. Section II discusses the literature on 1) technology roadmapping frameworks; 2) innovation dynamics in developing countries; and 3) transition management of complex innovation systems. In Section III the conceptual framework for complex technology roadmaps in developing country context is presented, followed by a discussion on the research methodology in Section IV. In Section V the proposed technology management framework is evaluated against the Malaysia E&E sector sociotechnical transition roadmap. Section VI concludes this article.

II. Literature Review

In this section we briefly review the existing literature on standardization and customization of technology roadmapping approaches, the innovation dynamics in developing countries and we discuss the transition management for complex innovation systems in order to define key concepts on long range planning for complex systems.

A. Standardization and Customization of Technology Roadmapping Approaches

Technology roadmaps have proven to be successful in the standardization of approaches for technology planning in response to the market drivers. The motive for standardization shifted over time in terms of best practice perspectives (1987–2000), engineering perspectives (2001–2010), and organizational behavior perspectives (from 2011 onward) [8]. The best practice theoretical perspective was dominated by case studies of roadmapping practices within companies such as Motorola, Lucent, Philips, and so forth [9], whereas the engineering perspective sought to generate a body of knowledge that assisted with the "how" of roadmapping efficiently. Among some known processes developed were the "fast-start" technology roadmapping workshop techniques introduced by Phaal *et al*. [10]. The organizational behavior perspective balances technology scouting inputs with opportunity scouting inputs and this is achieved through the exchange and co-creation of innovation roadmaps with suppliers and other partners [9].

In addition to a drive toward standardization of technology roadmapping approaches, different technology management contexts also necessitate customerization of technology roadmaps to suit particular applications in terms of both architecture and process [11]. A customerization framework suggested by Lee and Park [12] recognizes the importance of a balance between full personalization and full standardization. We conclude that further research is needed with regard to customization of technology roadmapping approaches with respect to customerization by the industry and user groups, as well as visualization methods for high-quality roadmaps. Different levels of countries' development, evolving innovation models, and also the new era of the fourth industrial revolution, necessitate some reflection on the standardization and customization of technology roadmaps.

B. Innovation Dynamics in Developing Countries

A recent paper [5] derived a set of findings regarding the nature of an innovation profile from the perspective of the technology roadmapping community in South Africa, a study done as a case for developing countries. The first two findings dealt with innovation priorities at the country-level and private sector respectively, namely 1) The main innovation priority for technology roadmaps in developing countries is science-driven technological capability development and 2) The main innovation priority for technology roadmaps of private sector companies in developing countries is technology development and market integration. These findings capture two roadmapping perspectives, namely the technology and research perspective of the public sector, as well as the commercial, strategic, design-development and production perspectives by the private sector. The following further three findings from [5] dealt with issues of actual or perceived innovation competitive advantage in developing countries. These critical competitive advantages are the external network of partners, window of opportunity and emerging/ converging technologies. The following is a summary of these findings.

1) External networks of partners are valuable sources of competitive advantage for innovation programs that are part of technology roadmaps in developing countries.
2) Timing of the innovation landscape's window of opportunity is important for technology roadmapping in developing countries in order to create the innovation competitive advantage.
3) Novel innovation pathways are likely to result from technology roadmap innovation programs that make use of biotechnology, nanotechnology, and environmental technologies.

C. Transition Management for Complex Innovation Systems

Innovation systems in developing countries represent a complex environment due to persistent challenges that are deeply embedded in societal structures, uncertainty due to hardly reducible structural challenges and difficulty to manage diverse stakeholders with different interests [13]. Such complex environments can be better understood through the use of complex systems theory. A complex system is adaptive to changes in its local environment, it is composed of other complex subsystems and it behaves in a nonlinear fashion such that a change in the outcome is not proportional to a change in input [14]. Some characteristics of complex systems are emergent properties that are observed at the system level, but not at its individual parts [15] and have adaptive and dynamic behavior that maintains a stable equilibrium state through resistance and resilience [16]. Lucas [17] described some complex system characteristics which were later grouped by Bertelsen [18] as composed of autonomous parts with certain behaviors (nonstandard, co-evolutionary, self-modification, downward causation, and self-reproduction) and in terms of nonlinearity (emergence, multiple alternative attractors, phase changes, and unpredictability). The theory of complexity can be used in describing systemic failure and undesirable lock-in that are typically experienced by the innovation systems of the developing countries.

Through the usage of the multilevel perspective (MLP), which will be discussed as part of conceptual framework, transition of complex systems takes place at multilevel which includes niche innovations (first level), sociotechnical regimes (second level), and sociotechnical landscapes (third level), hence successful transitions are a result of interactions among these three levels [19]. Users of the proposed framework therefore include those role players responsible for the policies, regulations, and activities on the various layers in the MLP. Transition-based strategies and policies are aimed at stepping away from incremental developments along "business-as-usual" trajectories [20] by inducing and guiding complex processes of sociotechnical change by means of deliberation, probing, and learning.

Transition and complex system theories' concepts have been applied indirectly to technology roadmapping literature by several scholars [2], [21], [22], focusing more on technology lifecycles and anticipation of technological discontinuity. This research incorporates these theories on each layers of the roadmap, beyond technology forecasting and discontinuities. As innovation processes are getting more complex, the transition and complex system theories can be useful for both developing and developed countries. While developing countries' interests are in nurturing the niche innovations for upscaling, the firms in developed countries would like to prepare themselves for future emerging technologies and technology catch-up.

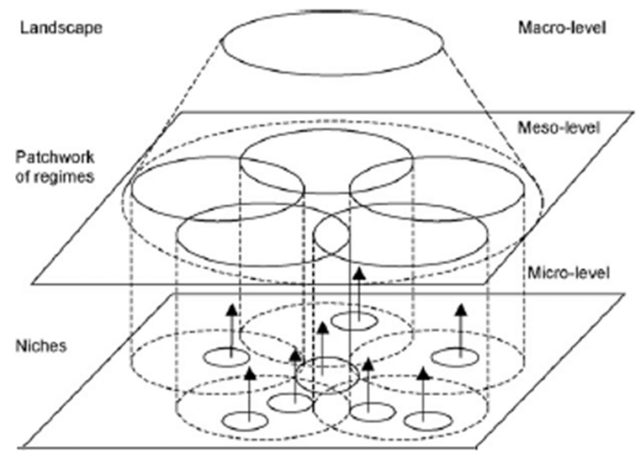

Fig. 1. Multilevel analysis framework [29].

III. Conceptual Framework for Sociotechnical Transition Technology Roadmaps

Technology convergence in the complex environment of developing countries, calls for a technology roadmapping framework that takes into account challenges such as a lack of innovation and entrepreneurship capacity, policy uncertainty and a less integrated market. Various scholars [23], [24] investigated a wide range of technology management frameworks which are ideal for these complex environments and one of the most relevant is complex systems. As technology roadmaps are concerned with future market and technology perspectives [2], innovation catch-up strategies and technology leapfrogging theories are relevant in building a technology roadmapping framework for developing countries. Transition management theory is relevant in defining a framework for a fundamental shift from an undesired innovation state to a desired state [25]. The main objective of this section is to link these various theories with the existing formal technology roadmapping theories on the roadmapping process and format, in order to derive a standardized technology roadmapping framework which is ideal for developing countries and technology convergence.

A. Multilevel Analysis Perspective of Complex Innovation Systems

The MLP theory, as depicted in Fig. 1, has been used to analyze complex innovation systems. According to Geels [26], MLP pragmatically uses insights from evolutionary economics, sociology of technology, history of technology and innovation studies. It distinguishes three analytical and heuristic levels to understand system innovations, namely: niche innovations (microlevel), patchwork of regimes (mesolevel), and innovation landscape (macrolevel). In this framework, the novel configurations are generated at the niche (micro) innovation level, which depends on an established regime at the mesolevel and the innovation landscape at the macrolevel [27]. These three levels are part of a sociotechnical regime which incorporates technical and social issues. The social aspects such as rules, collaboration, and competition are often overlooked by technical stakeholders [19].

It should be noted that in this model no central agent at macro, meso, or microlevel can unilaterally determine the outcomes of the innovation system, as the incumbents can be influenced by disruptive innovations from niche innovators or by changes in the innovation landscape. A key assumption for the purpose of this article is the fact that most developing countries' innovating organizations are on the niche innovation level, at the periphery of leading global innovators [28].

The MLP is important for technology roadmapping in developing countries as the dominant technology roadmapping literature is based on the needs of incumbents to respond to future market needs and to protect themselves against current and future competitors, for example the Motorola Technology Roadmap [30]. According to the findings of a study commissioned in 2003 by the Dutch Ministry of Economic Affairs on 78 technology roadmapping initiatives, one of the best practices is to launch the technology roadmapping activities within an existing "social infrastructure" [31]. For niche innovators, especially those with disruptive innovations, such "social infrastructure" might not exist and it might need to be built from scratch.

B. *Leapfrogging as a Technology Catch-Up Strategy*

Technological leapfrogging assumes skipping of industrialization trajectories followed by developed countries and to leapfrog directly into a new innovation regime as part of new capacity addition. It can enable developing countries to be significantly innovative role players on established global markets, but also on the new markets created by the shifting innovation landscape and advancement of niche innovations. In order to achieve leapfrogging, the following conditions need to be met:

1) a shift toward new sustainable production approaches;
2) an action from the outset;
3) technology transfer from developed economies;
4) strengthening of the incentive regime;
5) international assistance [32].

Leapfrogging has shown to be instrumental in allowing a set of follower economies to reach the next rung of sustainable productions 30 years in advance of the most developed economies [33]. The fourth industrial revolution, global economic recession, climate mitigation, and recently COVID-19, are among several megatrends shaping the global innovation landscape. The phenomena of technological paradigm shifts open a window of opportunity for latecomer firms to realize technological leapfrogging by importing emerging technologies from developed countries [34].

C. *Proposed Technology Roadmap Format for Complex Systems of Innovation*

A simplistic, generic technology roadmap output format has been the reason for the increasing popularity in using technology roadmapping techniques in long-range technology planning. However, for complex innovation systems in need of transition from poor global competitiveness to mainstream innovation, there are other key issues that need to be incorporated into the technology roadmapping format shown in Fig. 2. The technology roadmapping format proposed in this article is derived from Genus and Coles [29]. The key components of transition on the horizontal axis are the predevelopment of innovation niches, the take-off phase, acceleration phase, and stabilization phase [35]. These resemble the life cycle phases of development, introduction, growth, and maturity.

During the predevelopment phase, networks and partnerships are important. Technology sources can either be in-house or outsourced and the same goes for manufacturing capability. This phase communicates to the stakeholders the innovation niches that will be experimented in order to derive the knowledge of what works and what does not work. The niche innovations are shown along with the dominant innovation regime in order to benchmark and to deduce plausible future technological paths in a business-as-usual environment. A parallel roadmapping effort that also considers the dominant innovation value-chain is useful for technology planning purposes based on the fact that this represents the best available product technology platform preferred by customers prior to the transition point.

In the initial version of a technology roadmap, an emergent innovation value-chain can represent the ideal emergent innovation standards that are necessary for a successful transition. From the knowledge gained during the predevelopment phase, the roadmap can be updated for the take-off and transition phases. The transition point is where the transition takes place during the acceleration phase.

D. *Proposed Technology Roadmapping Process for Complex Innovation Systems*

The technology roadmapping framework for developing countries is developed with a generic technology roadmapping process [35] as a starting point (see Fig. 3). This approach was followed by various scholars in customizing the technology roadmapping process [37]. The process has three main phases, namely

1) the preliminary activities;
2) technology roadmap development;
3) follow-up activities.

Even though Walsh [38] recognized that a traditional technology roadmapping approach is not suitable for a disruptive technology roadmapping process, a key observation is the fact that there is nothing wrong with the utilization of technology roadmapping techniques, but rather with a blind application of these techniques in cases such as a disruptive technology base. To address this concern, the proposed process for technology roadmapping in complex innovation systems considers existing theoretical frameworks such as complex systems and transition management to reflect developing countries' innovation environments. The format that is presented in Fig. 2 simply summarizes an outcome of the roadmap and there are vast amounts of analyses, discussions, and workshops that need to take place prior to that to achieve this consolidated vision. Technology roadmaps are deceptively simple in terms of format, but their development poses significant challenges [2].

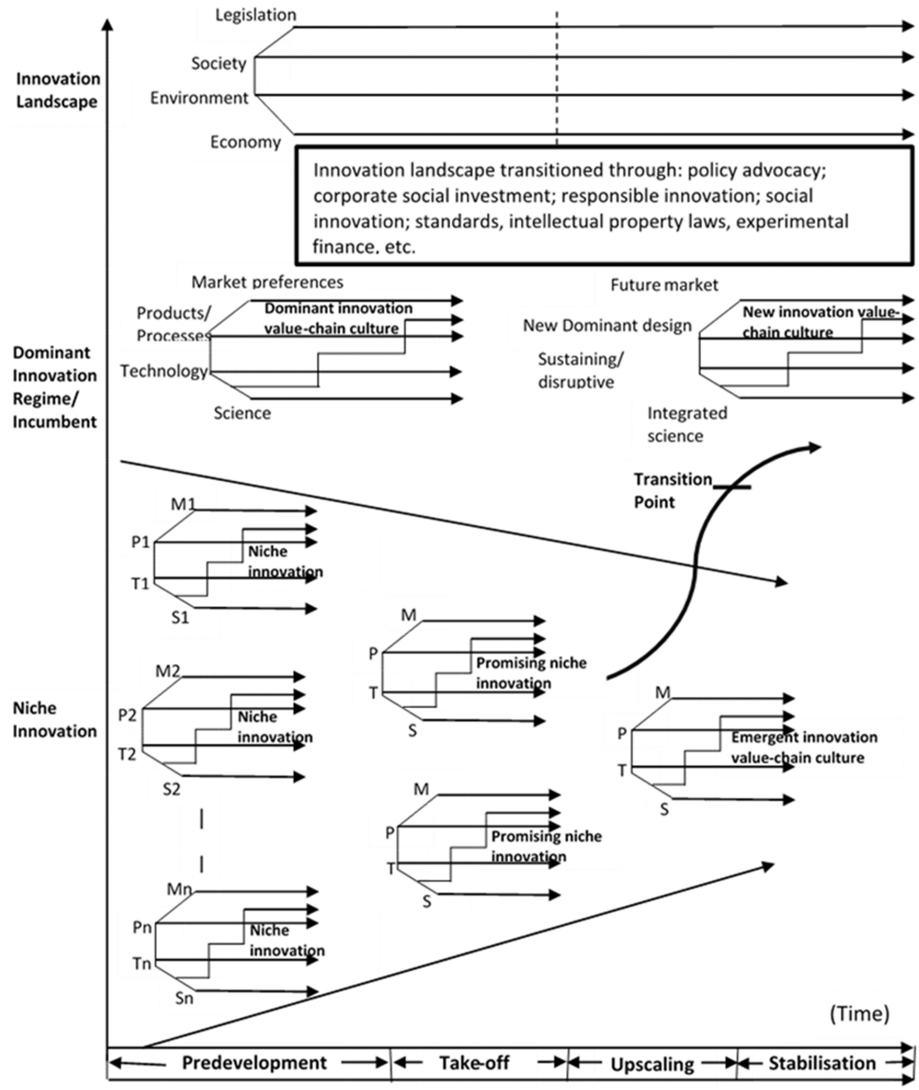

Fig. 2. Format for roadmapping complex innovation systems.

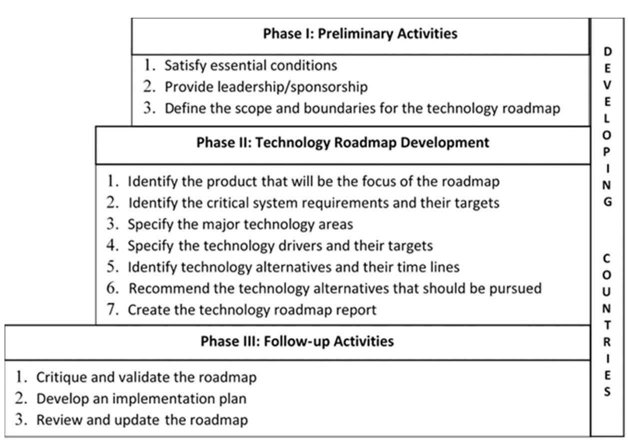

Fig. 3. Three phases of the technology roadmapping process [36].

In a recent study [39], a set of standardized principles were derived for technology roadmapping processes in developing countries. The following two principles dealt with the nature and characteristics of technology roadmaps in developing countries.

1) First Principle: Converging technology roadmaps are dominant in developing countries. These technologies could be a mixture of imported and locally produced technologies and they can have different lifecycle stages. Another important characteristic of converging technologies is that they can complement or compete with each other. A stable product-technology platform is not always a necessity due to a wide range of possible product portfolios.
2) Second Principle: Private sector technology roadmaps in developing countries are geared more toward technology leapfrogging in relation to the public sector technology roadmaps. Some elements of technology leapfrogging include more gearing toward the use of externally acquired technologies as opposed to the internal development of technologies through research and development. Therefore, an external scanning of technology trajectories

becomes important during a process of technology roadmap development. A multinational cooperation in developing countries can also achieve technological leapfrogging through internal acquisition of technologies from their parent companies.

These last three principles from [39] dealt with the issue of critical factors for successful technology roadmaps in developing countries.

1) Third Principle: In developing socio-technical transition-based technology roadmaps for developing countries, there should be a balance between the involvement of stakeholders from a dominant product-technology platform and those who seek new modes of innovation. The involvement of incumbents is important if technology leapfrogging is to be realized and also to ensure access to the global innovation value chains. Niche innovators with new technologies provide a mechanism to bring distinct technologies which might disrupt or modify the existing global innovation value chains in favor of a roadmapping organization within a developing country.
2) Fourth Principle: Scenario planning is an appropriate technique to use for selection of technologies and products that are part of technology roadmaps in developing countries. This considers a variety of landscape factors, unpredictable response of the incumbents and multiple converging technologies with uncertain outcomes.
3) Fifth Principle: Monitoring and update of technology roadmaps are critically important for transition-based roadmaps in developing countries, and such functions should be championed by the owners of the roadmap. A proper monitoring and evaluation system generates information for decision-making during the various phases of transition management. Such information can also provide a signal if a certain scenario kicks-in and a particular pathway needs to be adopted.

1) Preliminary Activities: During the preliminary activities, the following activities, based on the technology roadmapping principles discussed above, should be considered.

1) *Satisfy essential conditions*: Ensure that there is a clear case for the transition from the current dominant innovation regime to a desired future state. Situation analysis of the roadmapping organization or the beneficiary organization is important to understand the current or potential organizational capabilities versus that of the incumbents and to assess the window of opportunity within the innovation landscape.
2) *Provide leadership and sponsorship*: The successful technology roadmapping steering committees are those that are formed with the external partners. However, one should consider the transition objective and influence of the three layers of a complex innovation system (innovation landscape, dominant innovation regime, and niche innovators). The Third Principle postulated above suggests that there should be a balance between an involvement of stakeholders from a dominant product-technology platform and those who seek new modes of innovation. The leadership for the technology roadmap is also linked to the sponsorship type as it has been shown that the type of a roadmap sponsor influences the focus and the scope for the roadmap. The executive leadership should articulate the long-term vision and strategic objectives of the roadmapping organization and industry.
3) *Define scope and boundaries for the technology roadmap*: The scope of the roadmap should include a relatively longer time line, which is typically 20–25 years for the transition-based technology roadmaps, although the private sector organizations might seek to leapfrog through a relatively shorter time period (Second Principle), provided that the leapfrogging conditions are fulfilled as suggested by Perkins [32]. The scope and boundaries should be explicit about a paradigm shift being sought, namely incremental innovation on the existing product technology platform, insertion of an emerging technology or roadmapping of multiple emerging technologies. The latter is preferred for transition-based technology roadmaps (First Principle).

2) Technology Roadmap Development: The first step in the technology roadmap development, taking the above principles into consideration, is the identification of a product that would

1) *Identify the products that will be the focus of the roadmap*: Identify promising technology product platforms (niche innovations) and grand challenges. As this exercise is carried out, one need to be mindful of the dominant product technology platform and the structure of an existing innovation value-chain. Scenario planning can also be useful in this step (Fourth Principle).
2) *Identify the critical system requirements and their targets*: The blue-ocean strategic management tools such as the strategy canvas can help in identifying the critical system requirements and their targets for the niche innovations. A strategy canvas maps the opportunities that result from a gap between dominant products or services offered and the customer needs.
3) *Specify the major technology areas*: In identifying the technology areas, the emerging technologies in areas such as biotechnology, nanotechnology, and environmental technologies are ideal for the novel innovation pathways [5].
4) *Specify the technology drivers and their targets*: Technology drivers relate to how the technology addresses the critical system requirement targets. The drivers are the critical variables that will determine which technology alternatives are selected [36] and they need to factor-in the organization's objectives.
5) *Identify technology alternatives and their time lines*: A set of scenarios need to be developed based on technology drivers and their valuation as well as the associated assumptions (Fourth Principle). As these scenarios unfold, niche technologies need to prove themselves as a viable alternative in order to be supported for upscaling.
6) *Recommend the technology alternatives that should be pursued*: The selection of technology alternatives should take into account the organization's objectives, transition objectives, and a cost–benefit tradeoff.

7) *Create the technology roadmap report*: The proposed transition-based technology roadmap format is recommended for a high-level visualization of the roadmap (see Fig. 2).

3) Follow-up Activities:

1) *Critique and validate the roadmap*: Finalize the technology roadmap assumptions through consultation with the stakeholders, even those who are entrenched on a dominant product technology platform.
2) *Develop an implementation plan*: A high degree of flexibility is needed to adapt to the changes in the innovation landscape and for the possible response by the incumbents (learning by doing). Executive support is necessary for success of the roadmap implementation.
3) *Review and update the roadmap*: The technology management tools such as the stage gate model can be used to review the evolution of roadmap implementation through various transition phases, namely predevelopment, take-off, upscaling, and stabilization. The Fifth Principle for technology roadmapping in developing countries mentions a need for the involvement of roadmapping owners for its monitoring and update.

IV. Methodology

In this article, the BFR methodology developed by the Malaysian government is used to illustrate an application of the framework for sociotechnical transitions in developing countries. The methodology adopted to evaluate the proposed framework against the BFR methodology responds to the main research objective of proposing a standardized framework for technology roadmapping of sociotechnical transition large-scale projects in developing countries. The framework, explained in detail in Section III, was developed from preliminary research that was done [5] in order to characterize the innovation dynamics taking place in developing countries. Five principles were derived as best practice for technology roadmapping in developing countries. The framework also provides a generic format for roadmapping of multiple niche innovations for sociotechnical transition-based technology roadmaps. In addition, a step-by-step guideline was proposed for the development of such roadmaps, incorporating the five principles postulated during the preliminary research.

To evaluate the proposed framework against the BFR methodology, we made use of both a quantitative survey and qualitative interviews in order to derive the innovation dynamics of the BFR methodology from the perspective of the technology roadmapping community of which the findings have been discussed as part of the literature review in Section II. In order to verify the appropriability of the proposed technology roadmapping framework, the Malaysia's sociotechnical transition program, which was developed independently of this framework, is superimposed on key the aspects of the framework to check for the similarity and differences. The evaluation process followed the three phases of the technology roadmap development process as depicted in Fig. 3. We focused on the E&E sector, one of the 12 National Key Economic Areas prioritized by the government of Malaysia in collaboration with the private sector. The main sources of information for this case study have been interviews with the senior consultants in Malaysia and Russia that were part of the team driving Malaysia's transformation program, as well as critical analysis of relevant documents.

V. Sociotechnical Transition Roadmap: Malaysia's Electronics and Electrical Sector

Malaysia was selected as a case study for testing the standardization of the proposed technology roadmapping framework based on the following reasons:

1) Malaysia being a developing country;
2) having a clear vision for the transition of a sociotechnical system;
3) historical complex macroeconomic challenges;
4) consideration of data and information availability on most components of the proposed framework.

In the absence of a standardized framework for a pathway towards the sociotechnical transition, Malaysia had to start on a clean slate in its quest to transition from a middle-income to a high-income country. In the Sections V-A to V-D, the Malaysian BFR program is evaluated against the key aspects of the proposed framework as discussed in Section III-D and Fig. 3.

The process consists of eight key steps, namely

1) determine strategic direction;
2) organize Lab sessions (that can typically be in the form of workshops or focus groups) for intensive problem-solving, rigorous analysis and stakeholder engagements;
3) organize an Open Day for public announcement of Lab outcomes and recommendations;
4) develop the roadmap and associated documentation;
5) outline the Key Performance Indicators;
6) do roadmap implementation;
7) conduct audits and validation by international panels of experts;
8) compile an annual report [7].

Most steps of the BFR has some resemblance to the technology roadmapping's key steps such as preliminary activities, roadmap development and follow-up activities. The Lab sessions are very similar to those used in roadmapping approaches. The preliminary activity is the first step of the BFR methodology, namely: determination of strategic direction. The follow-up activities include roadmap implementation, conducting of audits, and validation by international panels of experts and compiling of annual reports.

A. Preliminary Activities for the Electronics and Electrical Sector Roadmap

1) Satisfying of Essential Conditions: A first requirement for a sociotechnical transition technology roadmap is a well-articulated vision for the intended transition. For Malaysia's E&E sector, the vision was to strengthen capabilities across the value chain, especially in the higher value-added upstream activities [40]. This was part of the Economic Transformation Program (ETP) with the objective of transforming Malaysia into a high-income nation by 2020. The demanding challenges that Malaysia faced in its electronics subsector included the following.

1) High exports vulnerability (electronics constituted approximately 60% of its exports of which 40% went to the United States).
2) The emergence of China as a new competitor on low-end, assembly-type volume manufacturing.
3) The country was yet to develop a sufficiently diversified and deep industrial structure to induce a critical mass of corporate investment in specialized skills and capabilities [41].

A significant challenge facing the EE sector in Malaysia was an inability to maintain growth in the face of competition from China, Taiwan, Singapore, and other Asian countries [40]. Furthermore, the E&E sector, whose exports were on a decline, traditionally focused on assembly, the lower value-added part of the industry, while countries like Taiwan, South Korea, and Singapore have captured the higher value-added activities in R&D, design and manufacturing. Lastly, under the proposed sociotechnical transition roadmapping framework, one of the essential conditions is to determine if the window of opportunity exists. Malaysia's E&E sector faced an upgrading challenge at the beginning of the transformation program. The common strategies used by developing countries' electronics firms in dealing with this upgrading challenge included four models, which are as follows:

1) global expansion through the acquisition of declining brands (emerging multinationals);
2) separation of branded product divisions from contract manufacturing (original design manufacturing spin-offs),
3) successful mixing of contract manufacturing and branded products (platform brands) for contractors with customers not in the electronic hardware business;
4) the founding of factory-less product firms that rely on global value chains for a range of inputs, including production [42].

The 2008 global economic crisis provided a window of opportunity for Malaysia's E&E sector for acquisition of multinational brands that were in decline.

The E&E sector upgrading roadmap did not explicitly analyze the existence of the window of opportunity as this concept is also not included within the BFR methodology. A more detailed analysis of the window of opportunity would have perhaps identified declining global brands that could have been a target for acquisition by Malaysia's E&E sector companies.

2) Provision of Leadership and Sponsorship: The development of the E&E sector transformation roadmap for Malaysia was championed by the performance management and delivery unit (PEMANDU). This newly created operational structure was established to implement a transformation program through the BFR methodology in which McKinsey played an important role [43]. McKinsey had previous experience in assisting the U.K. government in developing a national performance indicator framework for economic growth programs. Several countries executed projects to develop national performance indicator frameworks but usually this was done for specific sectors with its own specific frameworks. The E&E sector faced the same problem. Another key stakeholder that became involved with the development of the E&E sector sociotechnical upgrading roadmap was Malaysia Academy of Sciences, through its Mega Science Framework Study on National Sustainable Development (2013–2050). There is no evidence of the involvement of the key private sector stakeholders in leading development of the roadmap for the E&E sector upgrading from the onset. However, there was extensive consultation with the private sector and it was expected that most of the projects and opportunities identified would mainly be funded by the private sector. The phenomenon of the private sector key role players being expected to implement and sponsor a roadmap, even though they are not part of steering committees, is a weakness that seems to manifest itself on technology roadmaps from developing countries [39]. As PEMANDU was the main driver for the sociotechnical transition, there was no effort to include the external network of partners from the E&E sector incumbents and the niche innovators in the steering committee, as is required by the third principle of the proposed sociotechnical transition roadmapping framework.

TABLE I
MALAYSIA'S GOVERNMENT TRANSFORMATION PROGRAM ROADMAP [45]

	Period	Target
Horizon 1	2010 – 2012	- GTP to serve as a new engine for change and to quickly deliver substantial outcomes to the people - Continuation of existing efficiency measures to improve government productivity
Horizon 2	2012 – 2015	- More pervasive change within government - Significant improvement of important aspects of daily life - Evolution of economic structure into higher value-added sectors - Further enhancement of government productivity
Horizon 3	2015 – 2020	- Fundamental changes to the Malaysian society - High level of prosperity: Better public services Small and agile government - Increasing usage of public-private partnerships to provide services efficiently - Innovative and people-centered models of public service delivery

To overcome this shortcoming, the Electrical and Electronics Strategic Council (EESC) was established in 2015 to act as an advisory platform for the E&E industry for the remaining five years of implementation of the E&E sector transformation roadmap. Some of the functions of this Council were to identify the gaps within the E&E ecosystem and to establish subworking groups to address specific needs for the industry to move forward in the next five years [44].

3) Defining the Scope and Boundaries for the Technology Roadmap: As Malaysia's E&E sector technology roadmap was part of a large-scale Government Transformation Programme (GTP), its time horizon is linked to the one shown in Table I, a 10-year period which is divided into three phases: Horizon1 (2010–2012), Horizon 2 (2012–2015), and Horizon 3 (2015–2020).

The targets of Horizon 1 translated to an improvement of efficiency measures and productivity at the government and regulatory-level for the E&E sector. An outcome of these

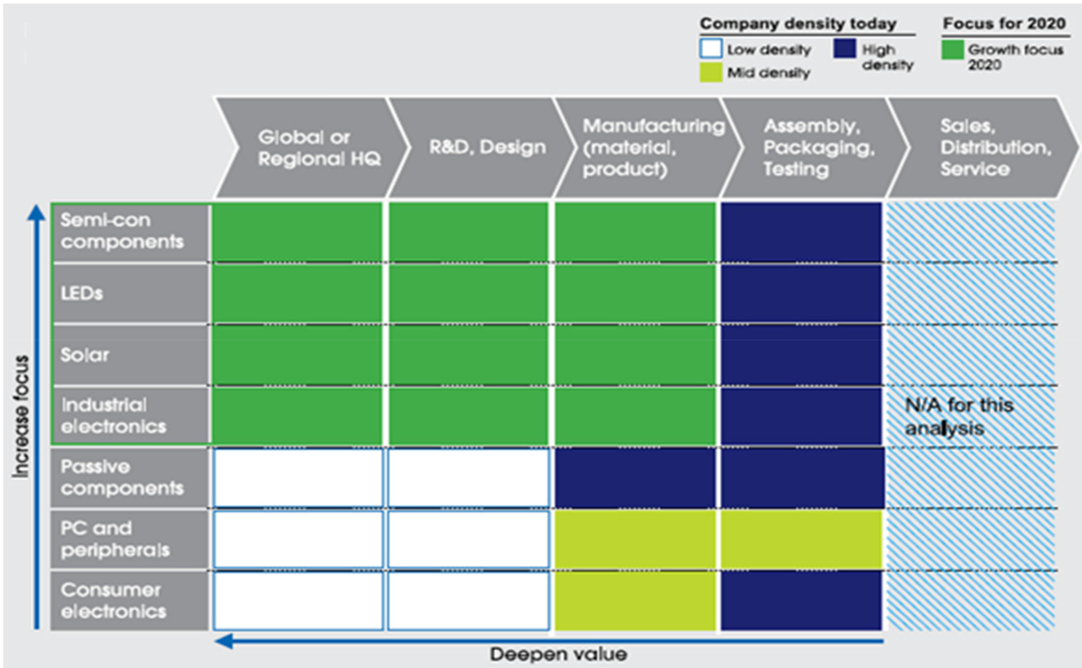

Fig. 4. Deepening value and focus of Malaysia's E&E sector [40].

initiatives was improved framework conditions at the innovation landscape level. Horizon 2 was aimed at all three levels of the multilevel perspective on sociotechnical transition as it involved accelerated transformation of government, society, and the economic sectors (involving incumbents and niche innovators). Horizon 3 was a beginning of a transition phase affecting the macro, meso, and microlevels of the innovation system. Horizon 1 involved mainly preparation of the framework conditions by the government and the estimated time horizon for the E&E sector technology roadmap was seven years. This time horizon was located midway between short and longer time period; hence, one would expect some element of technological leapfrogging from the private sector (Second Principle) as well as science and technology roadmaps from the public sector.

There is an evidence of technological leapfrogging intention by the Malaysian government considering 1) the relative shorter time period allowed for the E&E sector upgrading roadmap and 2) a focus to attract more leading multinational companies on the four geographical clusters, namely: Northern Corridor, Greater Klang Valley, Johor, and Sabah and Sarawak. The strategic intent of attracting foreign direct investment to create more Malaysian champions is in line with the Third Principle of the framework which suggests that the external network of partners is a valuable source of competitive advantage. The small and medium enterprises (SMEs) were expected to play a significant role in implementing the E&E sector roadmap [40]. This aligns well with the Third Principle of sociotechnical transition roadmapping framework, which suggests "a balance between involvements of stakeholders from a dominant product-technology platform and those who seek new modes of innovation."

4) Summary. Preliminary Activities: In summary, the preliminary activities that took place as part of Malaysia's E&E sector upgrading technology roadmap adhered to some extent to the sociotechnical transition technology roadmapping framework. This is not surprising if one refers to a first step of the BFR methodology, namely: "setting of strategic direction by determining the transformation goal from onset, the time period in which this must be achieved and key areas of focus to transform within the duration of the program" [7]. However, the BFR methodology lacks explicit strategic intent on involvement of an external network of partners and striking of a balance between involvement of the incumbents and the niche innovators such the SMEs. As Malaysia's sociotechnical transition program of the E&E sector also involved learning-by-doing, some of the enabling systems were put in place as the need arises (e.g., setting-up of the EESC).

B. Roadmap Development for Upgrading of Malaysia's Electronics and Electrical Sector

1) Identification of Products, Critical System Requirements, and Targets That Will be the Focus of the Roadmap: A technology space analysis of Malaysia's E&E sector is shown in Fig. 4, with targeted areas of growth toward 2020 shown on the top left area. The following were the levels of activity: high-density areas (mainly assembly, packaging and testing), medium-density areas (mainly manufacturing of PC peripherals and consumer electronics), and low-density areas (doing R&D and design as well as hosting of global or regional headquarters for passive components, PC peripherals, and consumer electronics).

Through the leadership of the private sector, the E&E sector's target was to focus on high value-adding activities for the semiconductors, light emitting diodes (LEDs), solar appliances, industrial electronics, and the home appliances

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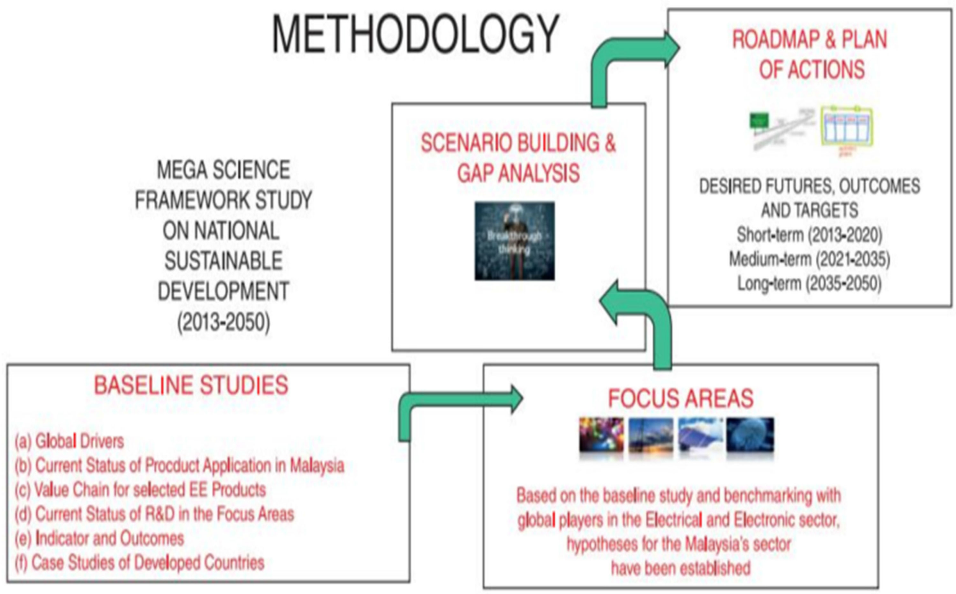

Fig. 5. Methodology of the mega science study for the E&E sector [46].

subsectors. These subsectors were chosen based on their attractiveness in terms of growth and size. With reference to the sociotechnical transition technology roadmapping framework, Malaysia seems to have adopted a technology catch-up strategy through backward integration of its E&E sector. There is no clear strategic intention of nurturing niche innovations that can significantly transform the sector.

As mentioned by one of the respondents interviewed: "the BFR methodology enables strategic coordination of various stakeholders to achieve big results out of already existing initiatives." Therefore, a shortcoming of BFR methodology is a risk of achieving only marginal competitiveness while competing directly within the space of the industry incumbents. The proposed framework provides for development of several niche innovations that can achieve tangible transition. Both strategies of incremental and radical innovations involve a certain level of risk and reward, hence the rational of the Third Principle stated in this article. This principle encourages a balance between involvement of stakeholders from a dominant product-technology platform and those who seek new modes of innovation.

An advantage of imitation innovation was that there was no need to identify the critical system requirements and targets for the products that would be the focus of the roadmap as the target products were already produced by the multinational corporations being targeted. With less uncertainty regarding the products that were the target of the roadmap, scenario planning was also not necessary (Fourth Principle).

2) Identification of Major Technology Areas and Drivers and Their Targets: In the absence of clear novel niche innovations on the original product technology roadmap for the E&E sector, the Malaysia Academy of Sciences took initiative through its Mega Science Framework Study on National Sustainable Development (2013–2050) to develop an improved, long-term technology roadmap for the E&E sector. As shown in Fig. 5, this framework incorporates the baseline studies of the E&E sector on global drivers, current status of product application in Malaysia, value chain for selected E&E products, current status of R&D in the focus areas, indicators & outcomes, as well as case studies of developed countries.

The improved roadmapping methodology by the Malaysia Academy of Science, a departure from the BFR methodology, introduced some missing elements of the sociotechnical transition technology roadmap in comparison to the original roadmap. Some of these improvements included the use of scenario planning (Fourth Principle), long-term public sector technology roadmap (Second Principle), and learning from the developed countries through baseline studies and benchmarking (Third Principle).

The baseline studies and benchmarking with leading global players in the E&E sector determined the focus technology areas for Malaysia in each subsector. The technology roadmaps developed for each subsector summarized the desired futures, outcomes and targets in the short-term (2013–2020), medium-term (2021–2035), and long-term (2036-2050).

C. Analysis of Malaysia's Overall Electronics and Electrical Sector Technology Roadmap

In this section, we analyze various elements of Malaysia's E&E sector roadmap in terms of the multilevel framework which incorporates the innovation landscape (macrolevel), incumbents (mesolevel), and niche innovations (microlevel).

1) Changing Innovation Landscape for the E&E Sector: Fig. 6 shows that the main innovation landscape factors that were dominant at the macrolevel were government, society, and economy.

These three innovation landscape factors are not necessarily similar to the ones shown in Fig. 3 as part of the proposed sociotechnical transition technology roadmap format as these depend on a country or sector' unique situation. Prior to Malaysia's

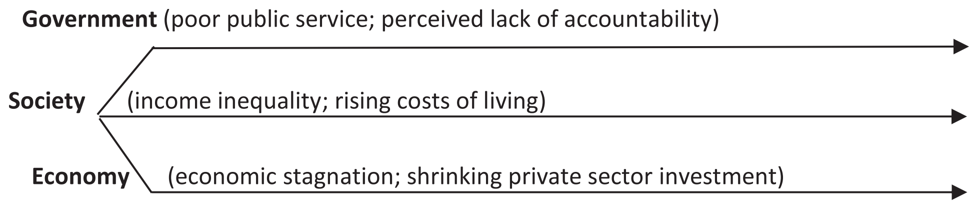

Fig. 6. Main innovation landscape factors for Malaysia.

journey into its transformation program in 2009, the country had a long history of income inequality, economic stagnation, poor public services, perceived lack of government accountability, shrinking private sector investment, and rising costs of living [43].

The transformation program in Malaysia involved leadership at the highest level of government. The Prime Minister of Malaysia (2009–2018) had a concept of "1Malaysia: People First, Performance Now" as "a program to promote harmony among the country's disparate ethnic groups, improve government services, and establish new, long-term plans to lead Malaysia out of the global economic crisis and ensure growth" [43].

2) Undesirable Status Quo for the Incumbents of the E&E Sector: As shown, there was a clear undesirable status quo for the E&E sector. The challenges identified at the market layer included high export vulnerability (due to high dependency on the United States as the single largest export destination), emergence of China as a new competitor on low-end, assembly-type volume manufacturing, and inability to maintain growth in the face of competition from China, Taiwan, Singapore, and other Asian countries. At the products layer, we stated that the E&E sector traditionally focused on assembly, the lower value-added part of the industry, while countries like Taiwan, South Korea, and Singapore have captured the higher value-added activities in R&D, design and manufacturing.

Under the 2010–2020 roadmap, the E&E sector regime was to be transformed through migration to higher value-adding activities and attraction of global brands. This roadmap is not specific about technologies as implicitly it is assumed that these will be brought along with the leading global brands. Therefore, the major weakness of this first roadmap is a lack of technology perspective, with more focus on market and products.

3) Niche Innovations for the E&E Sector: The niche innovations were identified in different stages including during the initial launch of the 2010–2020 roadmap and also through the roadmap developed by the Malaysia Academy of Sciences. The presence of several candidate niche innovations is in line with the First Principle of the sociotechnical transition technology roadmap. As expected, these niche innovations are at different life cycles. Some of these niche innovations are summarized as follows.

1) Upgrade of the photovoltaic (PV) industry: At the market layer, in order for Malaysia to be a world leader in PV by 2020, the focus would be on commercialization of breakthrough 3rd and 4th generation PV cell and inverter systems [47]. At the product layer, local product and system integration would be a focus in areas such as PV manufacturing, software, mounting, monitoring, BOS and power inverters. The applied research on 1st and 2nd generation PV cells would focus on development of wafer/ substrate manufacturing business, epitaxial wafer processing and LED and monolithic microwave integrated circuit device fabrication, whereas fundamental research would be directed toward 3rd and 4th generation PV cells [46]. '
2) New entry point projects (EPPs) launched in 2010: These included mature technology fabrication; assembly & test using advanced packaging technology; integrated design firms; silicon producers; solar module producers; LED front-end operators; LED packaging & equipment; local solid state lighting champions; test & measurement hub; wireless communication & radio frequency identification; automation equipment manufacturing; transmission & distribution companies; electrical home appliance manufacturing hub & international distribution networks [48].
3) Additional entry projects launched in 2013 in addition to the PV industry niche innovations: Additional projects included systems for the solar photovoltaic industry; electric vehicle component manufacturing; maintenance, repair and overhaul services via component manufacturing in the electric/ electrified railway industry and nanotechnology industry [48].

D. Validation, Implementation, and Update of the Roadmap

The responsibility for reviewing, validating, developing implementation plans and updating of Malaysia's transformation program and its associated sector roadmaps has been placed mainly in the hands of PEMANDU. This delivery and performance management unit, reporting directly to the office of Prime Minister, has been hailed as a great success. Through learning-by-doing, the EESC was established at a later stage to assist with the implementation and monitoring of the roadmap. This aligns well with the Fifth Principle of the sociotechnical transition roadmap. The main instrument for monitoring of the government transformation program was the annual reports such as the one for the National Transformation Programme and ETP. One of the monitoring tools used within the annual ETP progress reports was the ETP scorecard, which assessed the extent to which the planned Key Performance Indicators for each EPP achieved the desired outcome for the past year [48]. The EPPs under the ETP also changed over time, because some initiatives proved to be less successful than anticipated and were replaced

TABLE II
LEARNINGS FROM MALAYSIA'S E&E SECTOR ROADMAP IN RELATION TO THE PROPOSED FRAMEWORK

Principles	Preliminary Activities	Roadmap Development	Follow-up Activities
1. Converging technology roadmaps are dominant in developing countries.		There is a presence of several candidate niche innovations at different technology lifecycles.	
2. Private sector technology roadmaps in developing countries are geared more towards technology leapfrogging.	Mid-term roadmap of a 10-year period, with leapfrogging intent for the private sector and long-term (2013 - 2050) science and technology roadmaps for the public sector.		
3. In developing socio-technical transition-based technology roadmaps for developing countries, there should be a balance between the involvement of stakeholders from a dominant product-technology platform and those who seek new modes of innovation	There was no evidence of the inclusion of incumbents and niche innovators in leading technology roadmap development.	There was an intent of creating more Malaysian champions (incumbents) through foreign direct investment. The SMEs were expected to play a significant role (niche innovators)	
4. Scenario planning is an appropriate technique to use for selection of technologies and products that are part of technology roadmaps in developing countries.		Improved E&E sector roadmap by Malaysia Academy of Science included the use of scenario planning.	
5. Monitoring and update of technology roadmaps are critically important for transition-based roadmaps in developing countries, and such functions should be championed by the owners of the roadmap			Establishment of EESC for implementation and monitoring of the roadmap

with other efforts. For the E&E sector, five clusters of the EPPs were added in 2013, in addition to the 15 EPPs that were initially identified in 2010 [48]. One of the new EPPs was the enablement of industries through nanotechnology.

1) Overall Alignment of Malaysia's E&E Sector Roadmap to the Framework: Table II summarizes the alignment of Malaysia's E&E sector roadmap to the proposed sociotechnical transition technology roadmapping framework. The columns represent various stages of the E&E sector roadmap development and the rows are the key components of the proposed roadmapping framework.

As shown, most elements of the proposed framework were in place in the BFR methodology, except the exclusion of key role players (incumbents and niche innovators) in leading technology roadmap development. Another important observation is a fact that some of the key steps of the framework emerged at later stages as the roadmap was being developed. These include development of long-term public sector roadmaps (with scenario-based planning) and establishment of the EESC.

VI. CONCLUSION

With a quest for developing countries to customize technology roadmapping approaches in order to fit their innovation ecosystems, countries such as Malaysia developed an innovative novel approach, namely the BFR methodology. However, as it has been shown for the development and implementation of Malaysia's E&E sector transformation roadmap, these efforts are often through learning-by-doing, which involves a lot of trial and error. Even though the BFR methodology is more inclined toward more mature initiatives with the ability to achieve big results in a short space of time, a lack of novelty, which is a key requirement to compete as high-income country, was recognized at a later stage. These and other afterthought initiatives demonstrate a need for a standardized sociotechnical transition technology roadmap. The sociotechnical transition technology roadmap framework proposed in this article have accurately captured the key elements of Malaysia's E&E sector roadmap and in addition recommend elements not included within the BFR methodology.

An advantage of the proposed sociotechnical transition technology roadmap is the fact that it makes use of a standard technology roadmapping process with additional customizations that are ideal for the developing countries. Some of these customizations include the recognition of the role of both the public and private sector on large systemic projects, taking into account an influence of the innovation landscape factors on success of transition-based technology roadmaps, importance of nurturing the niche innovations, acknowledgement of the role of multiple emerging technologies for novel innovation pathways, factoring in an advantage of the window of opportunity and structuring the interaction of incumbents with the niche innovators. The recent outbreak of the COVID-19 global pandemic, coupled with fourth industrial revolution technologies, illustrates how the innovation landscape can have a huge influence on various sociotechnical transitions. Hence, further research is necessary to validate and expand this framework beyond just the developing countries. A limitation of this article is that the sociotechnical transition technology roadmapping framework was only evaluated against one project, namely the BFR. Future research could include testing of the framework against more projects in order to fully validate the framework as a standard framework for use in both developing and developed country context.

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