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Application of technology roadmaps for renewable energy sector

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A B S T R A C T

Technology Roadmapping (TRM) is a growing technique widely used for strategy planning and aligning technology with overall business objectives. Technology roadmaps are extensively used in many diverse fields at product, technology, industry, company and national levels. An increasing number of articles published on TRM and technology roadmaps indicate that there is a growing attention for TRM among the researchers from academia, industry and government. In this article, an overview of the application of TRM in renewable energy sector has been provided. After survey of the relevant academic literature and industry roadmaps, we tried to group the roadmaps related to the renewable energy technologies into national, industry/sector and organizational level roadmaps. Research findings indicate that goals and objectives of renewable energy roadmaps are different at these three levels. At national level, roadmaps focus on future energy security, energy dependence, energy policy formulation and environment protection. At industry/sector level, roadmaps are used to identify vision, common needs and evaluate barriers, constraints and risks faced by the industry from technical, political and commercial aspects. Organizational roadmap focuses on evaluation and prioritization of R&D projects to achieve the business goals. Similarly different methods, tools and approaches are used to develop roadmaps at different levels. Various other characteristics of these roadmaps are also discussed and analyzed. Research findings also indicate that greater numbers of roadmaps are developed for those renewable energy technologies undergoing rapid growth. Moreover, most of these roadmaps are developed in the regions where more research, development and deployment activities of renewable energy technologies is taking place.

1. Introduction

Technology Roadmapping (TRM) is a very flexible and powerful approach widely used in industry for strategy planning and integrating business and technology. TRM approach was formally developed and practiced by Motorola in the late 1970s to support integrated product technology planning and technology roadmaps have been used by a variety of firms, industries and countries for strategic and technology planning [1,2]. Although many articles quote Motorola as the initial implementer of TRM, we received anecdotal evidence that TRM were performed in the US by GE around the turn of the century (1900) and by the Aluminum industry in 1950's.

Former Motorola chairman Robert Galvin defined roadmap as “An extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of the change” [3]. James Winebrake defined technology roadmaps as “A future based strategic planning device that outlines the goals, barriers, strategies necessary for achieving a given vision of technological advancement and market penetrations”[4]. Institute for Manufacturing at University of Cambridge defined TRM as “A high-level planning tool that can be used to support the development and implementation of strategy and plans, as well as

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communication of the plan" [5]. Roadmaps forecast future market directions, technological developments, and help to make strategic decisions. Generally roadmaps are used to answer three fundamental questions: (a) Where are we going? i.e. what are our vision, mission, objectives, goals and targets etc. (b) Where are we now? i.e. present state of technology, products, markets etc., and (c) How can we get there? i.e. policy measures, action plans, R&D programs, long-term & short-term strategies etc [2,6–8].

Roadmap helps to provide a framework for future innovations in a number of key technology areas and ensure that investment in technology and research is linked to the business drivers and market trends. TRM provides a framework to link business and product plans directly to technology by establishing linkages between technological and commercial functions [8–12]. So TRM concepts integrate technology developments and business planning in order to achieve the overall business objectives. Product technology roadmaps require close co-operation between the marketing, product development and R&D functions. Roadmaps can facilitate decisions of resource allocation and ensure better investment decisions in the right technologies over the lifecycle of products and businesses [2,8,13,14]. In today's competitive business environment it is critical to make the right decisions at the appropriate time. Roadmaps also assist in filtering alternate technological options and as a result of this process decision makers can focus on promising technologies [9].

Roadmaps may be developed by aiming at customer requirements (market pull approach) or trying to exploit technological innovations which can result in new business opportunities (technology push approach). Therefore, development of good and effective roadmaps requires simultaneous consideration of market pull and technology push, and it is required to carefully balance both aspects [2,8,15]. Most of the successful roadmapping efforts integrate both technology push and market pull perspectives [11]. Garcia et al. defined technology roadmapping as a needs-driven technology planning process which helps to identify, select, and develop technology alternatives for meeting product needs, recommended its usefulness in current increasingly competitive environment, and highlighted the importance of preliminary and follow-up activities for technology roadmapping process [16].

TRM applications include business strategy development, policy formulation, product and technology planning, strategy planning, understanding technology trends, keeping track of product & technology breakthroughs, and prioritization of R&D and product development projects. Technology roadmaps are also used for enhancing communication and information sharing within a company or entire industry, defining problems and needs, identifying barriers and hindrances, investigating technology and market GAPs, establishing future vision and strategy, deciding short and long-term action items, assessing impacts of new technologies and market development, and helping mangers for decision making, resource allocation, program/policy support, and evaluation [2,8–10,14,17]. Therefore, TRM approach helps to plan future in a very systematic way. By identifying gaps in technology planning and market opportunities, companies can take better strategic decisions and accordingly plan resources allocation.

There has been an increase in the scholarly publications (journal and conference articles) related to TRM approach during last two decades. It shows that TRM has received an increasing attention among the researchers from academia and industry. Moreover it also highlights that there is an increase in use of roadmaps in various sectors. Fig. 1 highlights the scholarly articles related to TRM published from 1987 to 2009 and clearly indicates significant increase in publication of TRM literature from the year 2000 onward [18].

There are multiple methods and approaches published in the literature for developing the technology roadmap and it had been recommended to use appropriate roadmap type and methodology depending upon the overall goal and objective of the roadmap [9,10,19,20]. Research based on an analysis of 80 different roadmapping exercises concluded that there are number of good practices to implement TRM and it is not possible to declare one single best method or approach [21] and different perspectives can be used to develop technology roadmaps [22]. However, most of the TRM literature emphasize that the roadmapping process should start by identifying the stakeholder (within a company/corporation in case of organizational roadmap or from entire industry or sector in case of multi-organizational industry roadmap), bringing them together in brainstorming workshops to share their ideas for the future and defining the scope of the roadmap [2,4,6,8,13,14,23]. Therefore, roadmaps provide a useful means for integrating multiple perspectives for strategic planning and innovation processes. Harmon et al. highlighted the importance multi-perspective approach for evaluation, assessment and forecasting of promising technologies for the future and cited that the multi-perspective approach can be used for addressing sustainable energy issues [24]. Therefore, TRM process results in building consensus across the company or entire industry/sector by bringing together all key stakeholders and develops vision of the

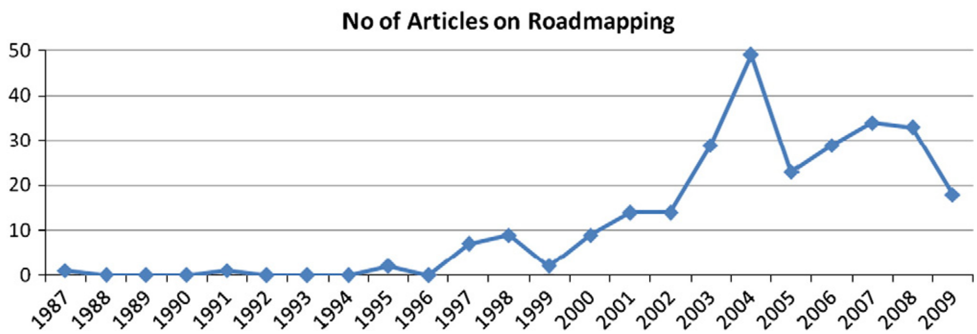


Fig. 1. No of articles related to TRM published in journals and conferences [18]. * Number of articles for the year 2009 is likely to increase by the end of year, data shows articles published till September, 2009.

future. TRM process significantly enhances the communication within the company or industry which is a valuable benefit [25]. It is also recommended that team members responsible for developing a roadmap should have an overview of concepts and techniques of the roadmapping process. Generally a facilitator having good knowledge of TRM process manages the entire process and keep participants focused. Bray and Garcia presented the following three major phases in the technology roadmapping process as shown in Table 1 [10].

Industry Canada presented guidelines for the development and evaluation of industry roadmaps after developing 26 industry roadmaps [26,27]. Objective of this TRM initiative was to support national innovation, identify industry needs for competitiveness, and explore opportunities for mutual gain. Three phases of TRM were described in the guidelines with detailed recommendations for the role of government and industry. It is recommended that government should facilitate development of industry roadmaps and provide necessary support throughout the TRM process [26]. In the evaluation framework it is recommended to monitor participation of industry and government in the TRM Process and analyze that actual results of the roadmap are achieved after the TRM exercise [27].

Technology roadmaps portray a concise and high level integrated view of future course of action. Usually roadmaps use a graphical approach which allows managers and decision makers to visualize the complete technology and market status, key milestones, decision points and strategy on one sheet of paper [2,8,23,28]. Graphical roadmap consists of a chart having information of different functions and perspectives against an agreed time line. Roadmap also visually highlights the linkages among markets, products, technologies, policy, resources and infrastructure, and identifies gaps, opportunities, barriers, and potential problems [8,13]. Therefore, roadmap is a very versatile tool and it can encompass a very broad scope of issues.

TRM also help R&D managers and policy makers to notice and track global trends in research of the promising emerging and disruptive technologies that have high potential in future. After TRM process all stakeholders have better understanding of current market and technology status, vision, goals, objectives, and future plans. Kostoff et al. elaborated that roadmaps provide a comprehensive overview of future technological landscape with an agreed view of vision to aid decision making [9]. By identifying critical technologies, alternative solutions and technology gaps, technology roadmaps provide vital information to decision makers at different levels to make better strategic technology decisions [16]. Fukuda et al. highlighted the application of technology roadmaps for R&D management and cited that roadmaps provide an opportunity for discussion among researchers and business-oriented people from academia, industry and government to find out reasonable ways for technology development [29]. Another reason of increase in the use of roadmapping method is due to the fact that it can be integrated with other management techniques such as Delphi method, portfolio methods, balanced scorecards, SWOT analysis, PEST analysis, QFD, innovation matrix, technology Intelligence techniques, bibliometrics analysis, citation network analysis, patent analysis, and product development stage gates [2,15,22,23,30–33]. These tools help participants of TRM process to better assess the technology landscape and market situation.

2. Application of TRM in renewable energy sector

2.1. Technology roadmaps in energy sector

Technology roadmaps have been widely used at product, technology, company, industry and national levels by many renowned companies, NGOs, academia, industrial associations, community groups, and governmental organizations to address diverse issues. Roadmapping approach has been used in a very diverse range of industry sectors including electronics, aerospace, defense, manufacturing, materials, paper products, software, semi-conductor, basic sciences, computing, information and communication technologies (ICT), energy, healthcare, agriculture, services, transport, environmental and climate change issues [2,8,9,14,15,34–36].

There has been significant increase in the use of TRM method during last ten years throughout the world. Analysis of approximately 1500 public-domain roadmaps indicates that most of the roadmaps are developed in twenty first century and use of roadmaps in various fields, industries and sectors is mentioned in Fig. 2 [36]:

Over the past decade there have been a lot of activities in the use of technology roadmaps in the energy sector and there are 170 public domain roadmaps related to energy ranked fourth in the graph. However, Science; Software, Computing & ICT; and Policy, Government & Community fields represents multiple sectors, therefore it can be inferred that energy is the single sector with the highest number of public domain roadmaps.

Table 1
Three phases in the technology roadmapping process [10].

Phases 1 Preliminary activity	• Satisfy essential conditions • Provide leadership/sponsorship • Define the scope and boundaries for the technology roadmap
Phase 2 Tech roadmap development	• Identify the “product” that will be the focus of the roadmap • Identify the critical system requirements and their targets • Specify the major technology areas • Specify the technology drivers and their targets • Identify technology alternatives and their time lines • Recommend the technology alternatives that should be pursued • Create the technology roadmap report
Phase 3 Follow-up activity	• Critique and validate the roadmap • Develop an implementation plan

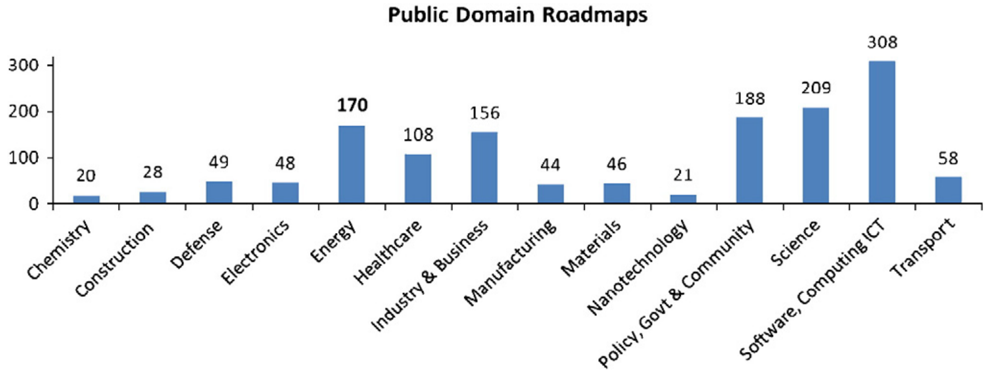


Fig. 2. Public domain roadmaps from various fields/sectors [36].

Further breakdown of energy sector roadmaps show that sustainable energy, hydrogen and fuel cell roadmaps are highest in number within the energy sector as shown in the graph [36]. It also indicates that there is more emphasis on research, development and deployment of renewable energy technologies and both public and private sectors desire to explore the future of renewable energy technologies. Breakdown of public domain energy roadmaps is shown in Fig. 3.

Energy is a key element for our society required for sustainable economic development. Renewable energy sources are the fastest growing source of energy in the world and various projections indicate that renewable energy resources will have huge contribution in the future [37,38]. Major factors influencing growth in the renewable energy technologies includes increase in cost of fossil fuels, depletion in the fossil fuel reserves, adverse environmental impacts, emission of greenhouse gases from combustion of fossil fuels, increasing air pollution, compliance with united nations framework convention on climate change (UNFCCC), increasing demand of energy, change in governmental policies towards renewable energy, independence from energy import, safeguarding and ensuring energy security [14,24,30,32,37,39]. The depleting reserves of fossil fuels, increase in population, improvement in standard of living and explosive economic growth of China, India and other developing countries is also causing energy shortages and raising concern about future energy supplies [38,40].

According to the International Energy Agency (IEA) total primary energy supply (TPES) for the world in 2007 was 12,029 MTOE (metric ton of oil equivalent) and renewable energy resources provided 12.7% share of TPES [40]. Renewable energy is derived from natural energy resources such as sunlight, wind, underground heat, biomass, or the flow of rivers and seas. Renewable energy technology alternatives include geothermal power, wind power, hydroelectric power, solar power (thermal and photovoltaic), biomass fuels, ocean/tidal power, fuel cells and hydrogen fuels. Energy statistics indicates that renewable sources like solar PV, wind, biofuel etc. have the highest average annual growth rate among all the energy sources during last five years [41]. The breakdown of TPES of the world is given in Table 2. Moreover, graphs attached as an Appendix A provide an overview of the overall energy picture of the world by showing primary energy supply of the world, average annual growth rate of all energy sources and renewable energy production mix of the world for electricity generation.

2.2. Review renewable energy roadmaps

In order to protect the environment and ensure supply of sustainable energy in the future, governments, industry and universities have initiated growing number of research and development projects on renewable energy technologies. IEA countries spend public sector energy R&D funds of almost US$ 10 billion/year [40] and global investment in new renewable energy capacity is steadily increasing with time as shown in Fig. 8 in the Appendix [42]. In United States many state governments have established renewable portfolio standards (RPS) mandating a fixed percentage of electric power to be obtained from renewable

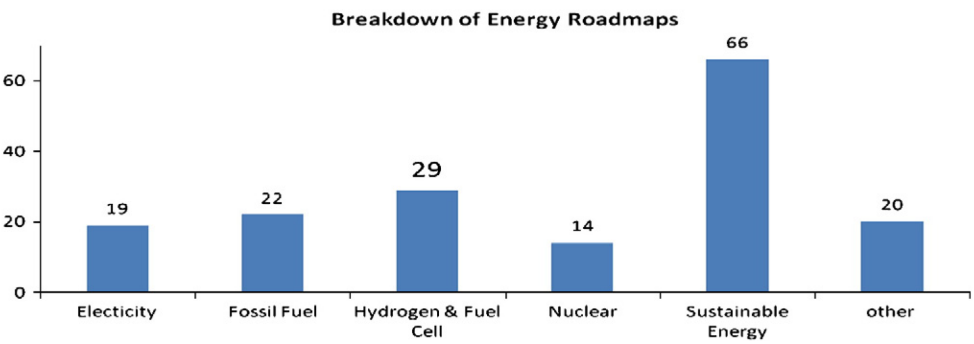


Fig. 3. Breakdown of public domain energy roadmaps [36].

Table 2
Share of world total primary energy (TPES) in 2007 [40].

S no.	Energy source category	Percentage of share
1.	Oil	34.0
2.	Coal	26.5
3.	Gas	20.9
4.	Nuclear	5.9
5.	Combustible renewable & waste	9.8
6.	Hydro	2.2
7.	Solar, wind, geothermal etc.	0.7

energy sources in order to increase contribution of renewable energy [43]. Moreover, governments are providing incentives to the end-users in order to ensure deployment of renewable energy technologies and as result of these efforts share of renewable energy has steadily grown over time. Technology roadmaps are extensively used for renewable energy technologies because of greater emphasis on research, development and deployment activities and all stakeholders desire to explore the future these emerging technologies. A review of the scholarly literature and technology roadmaps from renewable energy sector reveals that these roadmaps can be grouped into national, industry/sector and organizational level roadmaps. We now examine some of the germane roadmaps from each group.

2.2.1. National roadmaps

National roadmaps are generally issue oriented roadmaps which identify future national energy issues, their consequences and provide guidelines for policy makers and decision makers to overcome those issues and fulfill future needs. These roadmaps also provide a framework for public–private collaboration and establish directions for the growth of industry. Lee et al. presented the energy technology roadmap for Korea for next 10 years in order to provide guidelines for energy technologies development policy [30]. Roadmap provided insight information to Korean policymakers regarding the future of country's strategic energy development needs. SWOT analysis was also conducted to analyze present state of Korean energy technology base and subsequently roadmaps were made for 37 technologies selected from three broad areas of importance [30].

European Renewable Energy Council (EREC) developed renewable energy technology roadmap for 27 EU member states and established a target of obtaining 20% final energy consumption from renewable energy resources by 2020 along with interim targets for every country [44]. EREC roadmap recommended member states to develop national action plans with their individual targets for the shares of energy from renewable sources in transport, electricity and heating and cooling sectors by 2020. Current status of technology, expected future technological developments, current installed capacity of renewable sources, and projections were considered in detail and individual roadmaps were developed for bio-fuels, bio-energy technology, geothermal technology, solar thermal, photovoltaic technology, solar thermal, small hydropower, ocean technology, and wind technology with an aim to increase share of their energy contribution [44]. Similarly the commission of the European Communities prepared renewable energy road map for the 21st century for endorsement of the European Parliament with intent to assure EU citizens that their serious problems of climate change, environmental degradation and security of future energy supply are being addressed seriously [45]. Roadmap also provided a detailed analysis of the additional cost effects that society will have to pay for a 20% share of renewable energies under scenarios of varying crude oil prices and per ton carbon prices [45].

Greenpeace International and European Renewable Energy Council produced global energy scenario to provide guidelines for meeting CO_2 reduction targets and ensuring sustainable energy supply by establishing a target to cut global CO_2 emissions by almost 50% and generating half of the world's energy needs from renewable energy by 2050 under the energy revolution scenario [46]. It highlighted the catastrophic consequences to environment from usage of fossil fuel emission (greenhouse gases especially CO_2) and discussed the potential for renewable energy sources to overcome this problem by emphasizing on the right policy support, energy efficiency and renewable energy technologies, optimized integration of renewable energy and decentralized energy future [46].

Institute for Energy and Environmental Research (IEER) and Nuclear Policy Research Institute (NPRI) jointly developed carbon-free and nuclear-free roadmap to provide guidelines to U.S. energy policy and presented a very detailed overview, potential and viability of relevant emerging renewable energy technologies including wind energy, biomass, biofuels, hydrogen production, geothermal, wave energy, solar photovoltaics, solar thermal and energy storage [47]. Makhijani considered climate disruption, insecurity of oil supply and nuclear proliferation as the drivers for this roadmap and tried to create a vision of reference zero CO_2 emissions scenario, with no fossil fuels consumed and no nuclear power generated in the United States by 2050. Roadmaps also presented solutions for residential, commercial, transportation and industrial energy demand sectors and recommend detailed policy considerations to achieve this goal [47].

The Council of Australian Governments (COAG) made technology roadmaps for geothermal, hydrogen and high temperature solar thermal technology [48]. Development of these roadmaps was supervised by committees consisting of representative from concerned government departments, industry, R&D institutes, and environment groups. Australian hydrogen technology roadmap was developed with a vision to become among the world leaders in hydrogen technology and roadmap suggested role of Australian governments, industry and researchers in enabling and facilitating the development of a hydrogen economy in Australia [49]. Carbon abatement, pollution reduction, energy security and international competitiveness were considered as prime drivers for this roadmap. Bottom–up data gathering approach was used for creating this roadmap and stakeholders were asked to provide their views on internal and external industry landscape using SWOT analysis. Roadmap presented detailed strategies, options and activities related to policy framework formulation, knowledge building, competence building, market and supply chain development [49]. Objectives and drivers of the renewable energy roadmaps developed at national level are summarized in the following Table 3.

2.2.1.1. Other national energy planning approaches. Technology foresight and energy technology portfolio planning are among other common approaches used for formulating long-term energy strategy and planning. Czaplicka et al. applied Delphi method to create vision of energy sector of Poland till 2030 with an aim to provide direction for energy sector development in future and ensure energy security [39]. Scenarios were made and their results indicated priority pathways of future research for policymakers and decision makers [39]. Chen et al. used scenario analysis for long-term renewable energy technology portfolio planning for Taiwan [50]. Photovoltaic, solar thermal, wind, ocean, geothermal and bio energy alternatives were used in the study and three scenarios were developed based upon situation of global warming, breakthrough in renewable energy technologies and governmental policies in future. A committee of technical experts from diversified professional backgrounds assessed the importance and risks of renewable energy technology alternatives and subsequently developed a general strategic plan for the renewable energy technology portfolio [50].

2.2.2. Industry/sector roadmaps

Generally industry/sector level roadmaps are jointly developed by multiple companies or entire industry through industrial associations, consortiums, government departments or national research laboratories. Research indicates that it is much easier to launch TRM process by an active industry organization having a strong network structure within the related industry [21]. These technology roadmaps provide a detailed analysis of industry and emphasize on relevant emerging technologies, market issues, technology development strategy, R&D challenges, commercialization obstructions, and industry performance targets. Moreover these roadmaps also bring together industry and government to determine challenges and opportunities for the entire sector. Now we present a review of some industry roadmaps of different technologies and from different countries.

Canadian wind technology roadmap is an excellent example of reaching a consensus among industry, government and academia through a series of three workshops aimed at identifying key issues and recommendations for the growth of the wind energy industry in Canada [51]. Overall vision of the roadmap was to make Canada world-leading supplier of wind energy technologies and generate more than 20% of electricity needs by wind technology. Actions items with responsibility and timeframe were identified to achieve this overall vision. Roadmap recommended strengthening policy framework, creating centers of excellence, informing & engaging public, expanding role of industry, accelerating development of small turbine and supporting the demonstration projects [51].

Brenden et al. prepared a wind energy roadmap for Pacific Northwest and considered government policy, environmental issues, rising fossil fuel cost, dependency on imported oil, and prospectus of future business opportunities as the most important drivers [31]. In order to develop the wind energy roadmap for next 20 years, detailed technology assessment, SWOT analysis, PEST analysis and Porter's five force analysis were performed to identify the gaps in the product and technology and subsequently develop the wind energy roadmap [31]. Wind energy roadmap developed by International Energy Agency highlighted the critical steps and actions required to accelerate wind deployment. Energy security issues and environmental concerns were the main roadmap drivers and the cost of wind generation, system integration issues, transmission issues, energy market structure, and social acceptance of infrastructure were identified as major barriers [52]. Roadmap also provided an in-depth analysis of the current state of the wind industry and established targets for wind energy deployment between 2010 and 2050 [52].

Office of Energy Efficiency and Renewable Energy at the U.S. Department of Energy has developed many technology roadmaps related to various renewable energy technologies and energy efficiency technologies. National hydrogen vision and roadmap presented a framework for the coordinated long-term efforts from public and private sector required for hydrogen energy development and defined objectives and activities with consensus among government, industry, universities, national laboratories, environmental organizations, and other related parties [53]. U.S. Department of Energy conducted workshops to bring all stakeholders in order to develop the national hydrogen vision and roadmap with a goal to develop a hydrogen economy and identify associated challenges. Various scenarios were created to forecast future demand of hydrogen and explored wide range of activities required to realize hydrogen's potential in solving country's energy security and environmental needs. The high

Table 3
Objectives and drivers of the National Level Roadmaps.

Objectives	Drivers
• Energy policy formulation at national/regional level • To ensure energy security of the country or region • Identify and prioritize key technologies for future development • Presenting insight information to the policy and decision makers • Give direction to the national energy sector • Becoming a world leader in Renewable Energy Technologies • Renewable energy portfolio planning • Establishing future targets of obtaining energy from renewable resources	• Increasing cost of energy • Increasing price of oil • Fossil fuel depletion • Energy independence • Global warming and CO_2/greenhouse gases emissions • Pollution reduction • Compliance with International agreements e.g. UNFCCC etc. • Reducing reliance on imported energy • Avoiding proliferation of nuclear technology

cost of producing, storing and transporting hydrogen was identified as a primary challenge in this roadmap [53]. McDowall and Eames used roadmapping in combination with scenarios and foresight to review the future of hydrogen economy [54].

Vision 2020 is the lighting technology roadmap developed by the U.S. Department of Energy. It was also developed after series of workshops attended by more than 100 participants across the industry to generate consensus on the lighting industry vision from market and technology perspectives, identifying market and technological barriers and formulation of detail market transformation and technology development strategies to achieve goals for next 20-year [55].

The U.S. Department of Energy established 20% wind energy target to ensure generation of 20% electricity supply from wind energy by 2030 [56]. In order to achieve this 20% wind energy scenario it will be required to increase wind power capacity from 11.6 GW in 2006 to more than 300 GW over the next 23 years. Document presented in detail the current status of U.S. wind industry, potential of wind energy, types and issues of wind technology, transmission and integration of wind power, assessment of the technical and financial risk associated with wind energy, short and long term development needs and other impacts of wind energy [56].

The U.S. photovoltaic industry roadmap was developed as result of an industry-led effort to provide direction to the photovoltaic industry and government to facilitate research, technology development, manufacturing, applications, market growth and policy measures [57]. Vision of the roadmap was to provide competitive and environmental friendly electric power to the consumers from solar-electric power industry. Detailed roles and activities for the solar-electric industry and the government were identified in the roadmap in near-term (1–3 years), mid-term (5–10 years) and long-term (11–20 years) related to the technical, market, policy, and institutional issues. Roadmap established industry goal to generate 10% of U.S. peak generation capacity from solar PV by 2030 which is equivalent of approximately 180 million barrels of oil [57]. Detailed strategies were also formulated to achieve this ambitious target.

American Wind Energy Association developed small wind turbine roadmap with a goal of generating 3% of U.S. electrical consumption or 50 MW of electricity by 2020 and identified near to long term actions related to technology, policy and market [58]. Roadmap provided a detailed assessment of present state of wind turbine technology, industry, technological opportunities, market potential, policy measures, barriers to market development and strategies to overcome those barriers [58].

Biomass research and development technical advisory committee developed bioenergy and biobased products roadmap focused on research and development activities and public policy measures for developing policy for developing biobased fuels, power and products [59]. Committee consisting of experts from the entire biomass industry first identified the vision and then figured the barriers preventing the industry from achieving that vision through a series of meetings and focused research on feedstock research, processing, conversion and distribution sectors [59]. Lamb et al. used quality function deployment (QFD) and SWOT analysis to develop technology roadmap for the Wood Pellet industry of Oregon, USA [33].

Worldwatch Institute presented low-carbon energy roadmap in 2008 highlighting the catastrophic environmental condition due to high carbon emissions, potential renewable energy technologies with no-carbon and low-carbon emission technologies [41]. Christopher also emphasized the need of integrating renewable energy resources into the energy system and discussed the implications of two U.S. electricity generation scenarios for the year 2030 with different energy mix [41].

New Energy and Industrial Technology Development Organization (NEDO) in Japan established an investigative committee consisting of key figures from academic, industry and governmental circles in order to develop the PV Roadmap toward 2030 (PV2030) for Japan in 2004 [60]. After a series of six discussion sessions, committee was able to develop the roadmap with detailed description of expected position of PV power generation in 2030 along with future PV research and technological development issues and formulated tasks, targets and strategies of PV research and development for 2010, 2020 and 2030 [60].

Concentrating Solar Power (CSP) program of the U.S. Department of Energy developed roadmap for parabolic-trough technology after conducting workshops attended by experts from industry and research laboratories with a goal to evaluate the market potential, understand current state of the technology, perform detailed cost analysis, risk assessment, and develop a plan for advancement in technology [61]. Strategies for technology and market development were discussed by identifying activities for technology development and deployment along with near-term and long-term opportunities. Roadmap proposed that taxation policies like solar property tax exemption and sales tax exemption can facilitate deployment of technology. Roadmap provided a detailed technical analysis and identified cost reduction and performance improvement as key technology challenge hindering commercialization of CSP technology [61].

High temperature solar thermal (HTST) technology roadmap was developed to establish a plan for the development of HTST technology and research in Australia with a vision to strongly position Australian HTST industry in the supply chains for local and global energy markets by 2015 [62]. Prime drivers for HTST roadmap were reduction of carbon emissions and pollution, ensuring energy security and gaining international competitiveness. Roadmap provided an overview of HTST technologies from technological and commercial perspective, analysis of market growth potential and cost projections, key barriers and potential contribution of HTST to overall national energy needs. A consolidated SWOT analysis performed during two workshops helped the participants to identify and make consensus on strengths, weaknesses, opportunities and threats of Australian HTST industry and formulate appropriate strategies and policies related to competence and knowledge building, market and supply-chain development [62].

The Australian Department of Resources, Energy and Tourism developed the geothermal technology roadmap in order to provide development framework to geothermal industry with development timeline and a target of providing at least 7% of base load requirements from geothermal resources by 2030 [63]. Roadmaps presented the current status of geothermal development, nature and cost of available geothermal resources and key technological recommendations. All concerning issues pertained to geothermal exploration, environmental, potential tectonic setting of Australia, drilling and stimulation technologies, reservoir modeling and assessment, power conversion technology, and other emerging technologies were discussed in detail [63].

UK Energy Research Centre (UKERC) and UK DTI developed energy route maps for biofuels, fuel cells, geothermal energy, hydrogen energy, offshore and onshore wind energy, photo-conversion, solar PV, solar thermal and wave energy. UKERC developed the marine renewable energy technology route map after reviewing all previous marine energy technology reviews and conducting workshops with an objective to encourage cooperation and collaboration within the community and develop a coherent technical and business strategy [64]. Vision behind this activity was to ensure significant contribution to electricity generation in 2020 from the marine renewable energy in a cost competitive manner. Roadmap provided vital information to the policymakers and funding bodies. Moreover, in order to formulate the appropriate business and technical strategy various technology working groups were also established [64,65].

Sustainable urban energy planning roadmap was developed to better understand the energy needs of urban environments, increase local involvement in energy planning and provide guidelines to the decision makers [66]. Tools like alternatives analysis and scenario building were used to identify the steps that can most likely result in effective outcomes. Roadmap described the typical city energy use pattern and identified activities to achieve the short to long term goals of better understanding the environmental impacts and the operational energy needs of urban infrastructure. Roadmap provided better understanding of local and regional sustainable urban energy planning options in order to develop effective decision support tools and methods for sustainable urban energy planning [66]. Similarly technology roadmap for energy loss reduction and recovery was developed as a result conference attended by variety of industry representatives and researchers from national laboratories to identify and prioritize energy savings opportunities for technologies used in steam systems [67].

In renewable energy sector most of the roadmaps are developed at industry/sector level. Objectives and drivers of the industry roadmaps are summarized in the Table 4.

2.2.3. Organizational roadmaps

Daim et al. presented an example of implementing technology roadmap in an organization from government energy services sector and developed multiple roadmaps related to three groups i.e. renewable energy, energy efficiency and energy transmission technologies [68]. Paper presented a well structured and detailed procedure for implementing technology roadmaps in a company, highlighted importance of linking drivers and needs with overall organizational goals and recommended continuous monitoring and updating of the roadmaps [68]. Purpose of energy efficiency roadmap of Bonneville Power Administration was to ensure that the organization can achieve maximum benefit from its R&D budget by identifying high-priority promising technologies and providing a meaningful direction to the overall R&D efforts [69].

Renewable energy technology roadmap of Bonneville Power Administration was developed to facilitate better technology investment decisions and ensure utilization of R&D funding based on the organizational strategic needs identified in the roadmaps [70]. Separate roadmaps were developed for transmission grid-connected wind, ocean wave, in-stream tidal and solar photovoltaic energy resources after detailed overview of technologies and opportunities, in-depth analysis of challenges associated with research, development and deployment of these technologies [70]. BPA identified key sector actors heavily involved in renewable technologies from companies, universities, public agencies, national laboratories, advocacy groups, and private institutions and brought them together in workshops. Through workshops BPA identified and ranked the business drivers, business challenges, opportunities, targets, promising technologies, technological gaps that hinder deployment of promising technologies, and prioritized renewable energy-related R&D investments suitable for the company [70].

CLP is one of the largest investor owned power businesses in Asia providing electricity to 80% of Hong Kong's population and involved in electricity generation, transmission and distribution. CLP developed a technology roadmap to highlight the key technologies that the company will use to meet the targets set out in their climate vision 2050 [71]. Roadmaps presented the technology options for climate-friendly electricity generation, discussed major barrier to their development and deployment, and highlighted timeline of R&D phase, demonstration phase, and commercialization phase along with cost competitiveness analysis in each phase. Technologies identified by CLP includes wind power, concentrated solar power, geothermal energy, nuclear generation III, combined cycle gas turbine, advanced coal power, and heat pump water heater systems [71].

Table 4
Objectives and drivers of Sector Level Roadmaps.

Objectives	Drivers
• Establish common vision of the industry	• Change in government policies (favoring renewable energy technologies)
• Provide future direction to the industry	• Increasing energy cost
• Increase collaboration within entire industry and with government	• Mandatory renewable portfolio standards
• Propose conducive policy framework to the government	• Exploit new business opportunities
• Identify key industry challenges and barriers from technical & commercial aspects	• Environmental concerns
• Forecast future energy markets	• Become a competitive industry globally
• Identify industry needs to become competitive	• Seek benefit from emerging technologies
• Develop industry standards and future technology performance milestones	• National renewable energy targets
• Formulate action plans and strategies to accelerate industry growth and rapid technology deployment	• Achieve energy independence
• To ensure availability of skilled workforce required to support technology growth	• Harnessing available renewable energy resources
• Assess availability of supply chain infrastructure to supports future growth	• Creation of green jobs
• Assess long-term financing requirement for the industry	
• Create positive perception among public related to green energy technologies	

Scheemaker highlighted the importance of making hydrogen roadmaps for developing countries and recommended that hydrogen is a long-term solution to climate problems and developing a hydrogen economy requires support of visionary leaders from government and business sectors [72]. Shell established *Shell Hydrogen* in order to pursue business opportunities related to hydrogen and fuel cells. Company developed the world's first publicly accessible hydrogen station, established hydrogen stations for fuel cell buses under Clean Urban Transport for Europe (CUTE) initiatives and started joint ventures and partnerships with many world renowned companies in hydrogen fuel cell sector in order to get ready for hydrogen economy in future. Shell proposed establishing a new energy infrastructure for developing countries based on hydrogen and fuel cells and projected that with right support, there could potentially be 5–10 million fuel cell vehicles (FCVs) by 2020 globally and this number can grow beyond 100 million between 2030 and 2040 [72].

Objectives and drivers of the organizational roadmaps are summarized in Table 5. However, it is pertinent to mention that Table 5 is based on limited data as compared to data available for national and sector roadmaps presented in Tables 3 and 4. Generally organizational roadmaps are not published very often and kept confidential.

It can be seen from the above review of TRM literature and roadmaps, that these renewable technology roadmaps at different levels are developed for many diverse goals, objectives and needs. We have tried to review most of the accessible renewable energy roadmaps developed during last 10 years. Efforts are made to present roadmaps of different technologies developed in different countries/regions of the world by various types of organizations including governmental, non- governmental, industrial organizations and environment activist groups. In some cases one organization has made multiple roadmaps, so one or two roadmaps developed by one organization are discussed in this section. We shall now proceed to our analysis and discuss findings of the renewable technology roadmaps from all groups.

3. Analysis and discussion

We have provided an overview of many technology roadmaps for renewable energy sector and noticed that roadmaps have been extensively used in this sector. It is pertinent to mention that increasing contribution of energy from the renewable energy sources in the future is a multiple facets problem involving multiple stakeholders and roadmaps are considered an appropriate tool to address this complex issue. Research also indicates that roadmaps are critical when technology decisions are not straight forward [16]. The roadmapping process allows all stakeholders to present their perspective and facilitate consensus building among them. Roadmaps also provide a comprehensive framework to plan and coordinate all activities for technology development. Most of these technology roadmaps are developed based on needs and during the roadmapping process needs were linked with markets, industry, products, technologies, capabilities, resources, infrastructure, logistics, strategies and policies.

We have noticed that technology roadmaps are mostly used in the developed world mainly North America (United States and Canada), European Union countries and Australia. From Asia we find few roadmaps from Japan, South Korea, Hong Kong and Taiwan. Most of the R&D activities on renewable energy technologies are also being conducted in these developed countries. It indicates that technology roadmaps are closely related to the R&D programs, awareness, usage and deployment of that technology. Fig. 4 shows the regional distribution of renewable energy roadmaps.

There have been enormous growth in solar energy sector during the past five years with an average annual growth rate of more than 40% which is highest among all other energy technologies (renewable and non-renewable) [41]. Similarly our research indicates that highest numbers of technology roadmaps within the energy sector are related to solar energy technologies. Kajikawa et al. analyzed emerging technologies in energy sector by using citation network analysis and revealed that solar cell and fuel cell are most rapidly growing domains in energy research [32]. Our research also indicates that roadmaps related to these two technologies are in highest number. It again emphasizes our earlier finding that technology roadmaps developed in a certain sector are closely related to the intensity of research, development and deployment activities for that technology.

We have seen that the time duration of these roadmaps vary from 10 to 50 years. However most of the roadmaps have been developed for a time horizon of 10 – 15 years. Long range roadmaps also have short range and intermediate goals and targets. Albright mentioned that long range forecasts are suitable for the national or industry level roadmaps for government or social planning while shorter term forecasts are useful for business planning within a company [73]. It is found out that generally the national and industry roadmaps have comparatively longer time duration than organizational roadmaps. However, it has been also

Table 5
Objectives and drivers of organizational roadmaps.

Objectives	Drivers
• Communicate vision of the company • Link business and technology planning • Provide a meaningful direction to the R&D efforts • Prioritize R&D projects for the company • Identify technologies to invest in order to remain competitive • Identify key technical barriers and market challenges • Better resource allocation	• Increasing price fossil fuel • Pressure from government to generate renewable energy • Compliance with mandatory renewable portfolio standards • Become a technology leader • Enhance competitiveness • Environmental concerns • Creating positive image of company among customers • Seize new business opportunities • Exploiting new technologies

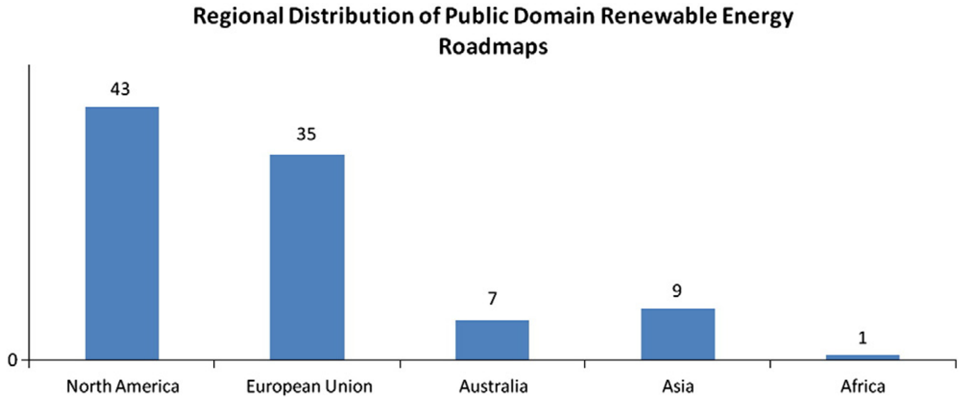


Fig. 4. Regional distribution of public domain renewable energy roadmaps.

observed that goals, targets, milestones activities and action items for the initial time frame of the roadmap are mentioned in more detail and for the later time frame activities and action items are broadly presented due to uncertainty. It is also important to periodically review and update technology roadmaps developed for long time duration.

We have seen that purpose and intended audiences of roadmaps also vary significantly. National and country level roadmaps are made to establish the national energy vision, goals and targets, provide guidelines to the policymakers, decision makers, governmental organizations, research laboratories and industry of the entire country or region (e.g. European Union). In national roadmaps various important national issues related to energy and their consequences are discussed in detail. Future energy security, energy dependence and environment protection are the main issues in national roadmaps. These roadmaps usually present high level strategies for developing or acquiring required technologies identified during the roadmapping process and provide a framework for public–private collaboration. These roadmaps establish through guidelines for policy and regularity requirements to ensure country's growth in a desired sectors.

Further analysis of national energy roadmaps indicates that the roadmaps developed by the governmental agencies emphasize more energy security, increasing energy cost, dependence on imported energy resources and national competitiveness issues and consider these factors as the prime drivers for national roadmaps. Whereas roadmaps developed by nongovernmental organizations (NGOs) give more emphasis on environmental concerns like global warming, environmental degradation, emissions of CO_2 and other greenhouse gases etc.

Industry/sector level roadmaps represent the collective knowledge of the entire industry comprising of multiple companies, government departments, research laboratories and universities. These roadmaps are intended to communicate to a broad audience with varying levels of knowledge about the issue and also used for policy debate and industry foresight applications. These roadmaps establish the vision of industry, provide detailed guidelines for R&D future of that technology and assess political and economic issues that can impact the industry in the long run. Sector level roadmaps identify the common needs, help to focus on critical technical issues and facilitate collaboration for developing required key technologies. These roadmaps also consider the technical, political and market constraints and future uncertainty. Roadmapping process also identifies key synergies, dependencies and gaps within that sector.

In renewable energy sector, industry roadmaps are generally emerging technology roadmaps which are different from traditional product technology roadmaps. Walsh conducted a case study of emerging technologies and stated that emerging technology roadmaps are different because focus of these roadmaps is not on the product/market but rather on forecasting the development and commercialization of a new technology [74]. Similarly it has been observed that renewable energy roadmaps primarily forecast the development and commercialization of renewable technologies and establish goals for technology performance improvement, market development and cost reduction over time.

Industry roadmaps also present the long term competitive position of the industry and technology. Key technical and commercial issues and barriers are analyzed with detailed root cause analysis. Subsequently issues are translated into activities with time line and responsibility. These roadmaps also perform risk assessment by exposing the technology and market gaps and other critical issues. Industry roadmaps are also used for lobbying lawmakers for making favorable policies. Often developing an emerging technology is very expensive or risky for one company due to technology and market risks. Industry roadmaps facilitate and foster cooperation and collaboration for joint technology development among multiple companies or entire industry and research laboratories from public and private sectors. Partnerships and mutual collaboration can greatly accelerate the pace of technology innovations and reduce the associated technical and financial risks.

Within the industry roadmaps some differences exist between roadmaps developed for different renewable energy technologies. For example roadmaps developed for wind energy which is a comparatively mature technology, provide very detailed industry performance improvement milestones, cost reduction targets and fairly accurate estimates for future resource requirement for technology deployment. Whereas for wave energy or hydrogen fuel cell technologies, which are not widely deployed, roadmaps emphasize more on forecasting future markets, expected technological breakthroughs that will help to commercialize the technology, market transformation aspects, developing supporting infrastructure, and initiating pilot projects for demonstrations purposes.

Various technology forecasting tools like patent analysis, bibliometrics data analysis etc. are also used during the development process of these emerging technology roadmaps.

It was revealed by comparing national and industrial roadmaps that there are some similarities and differences in these roadmaps. Both types of roadmaps are generally developed for a longer time horizon, create consensus among all major stakeholders, promote collaboration, and recommend policy measures. However, one major difference is that national level roadmaps discuss energy issues of the country and propose multiple technologies whereas industrial roadmaps provide an in-depth analysis of one particular technology. Major differences between national and industrial roadmaps are given in Table 6.

Organizational roadmaps are mainly used for future technology planning and making appropriate organizational strategy to achieve overall business goals. Companies use roadmaps to analyze alternatives, evaluate and prioritize R&D projects, facilitate technology investment decisions, comply with policy regulations and align technology investments with market and product needs. As a result companies formulate their technology strategy in accordance with organizational objectives. However, in renewable energy sector we found least number of organizational roadmaps. Some companies use roadmaps internally for planning and decision-making purposes and keep it confidential. Or it may be possible that some companies working renewable technologies are following the industry roadmaps. Moreover, most of the electric utility companies use integrated resource planning by evaluating many different options for meeting future electricity demands and select the optimal mix of resources to get reliable and least-cost electric power for their customers.

Strategic Business Development Department of Sandia National Laboratories formulated a very comprehensive technology roadmapping approach which includes identifying products and critical market requirements, specifying major technology areas and technology alternatives with recommendations, technology drivers and targets. It has been observed that the U.S. Department of Energy has used similar approach in developing some roadmaps of renewable energy technologies.

It has been revealed that workshops are mostly conducted during the process of developing national and industry roadmaps. Workshops bring together large group of stakeholders to share knowledge, creative thinking, review problems from multi perspectives and develop general consensus among all participants. Workshops help experts from diverse backgrounds to elaborate and forecast technology development in targeted areas. Therefore, workshops result in creating common vision, objectives and goals for the entire energy sector or industry. Moreover, workshops also provide networking opportunities, nurture communication and promote future collaborative development by industry, government and academia.

While reviewing the renewable energy technology roadmaps it has been observed that a variety of methods and tools were used in developing these roadmaps. Scenario based planning is widely used approach in renewable technology roadmaps, especially at national and sector level. Scenarios are generated to cater for uncertainty and facilitate development of responsive and robust strategic plans. Scenario analysis helps to identify multiple alternatives of the future state of technologies, needs, policies and environment. Generally good scenarios improve quality of roadmap by addressing uncertainty in future environment and needs. Some national and sector level roadmaps have also used SWOT analysis to evaluate strengths, weaknesses, opportunities and threats of renewable technologies. Participants in the workshops were asked to identify the internal and external factors that are favorable or un-favorable to the relevant technology, industry or country for achieving its vision, goals and objectives. It helps in matching capabilities and resources with the global competitive environment. We see few examples for using citation network and patent analysis to track and identify key emerging technologies and make better technology investment decisions. IP activity in a particular technology of interest is monitored at global or regional level for better forecasting. Citation and patent analysis is more common in emerging technologies. This technology intelligence data helps the experts to have an overview of the technology environment. In some roadmaps PEST analysis is used to understand and analyze the **p**olitical, **e**conomic, **s**ocio-cultural and **t**echnological environment. It's a good framework for scanning the external macro-environment but it is not very commonly used during the roadmapping process. Delphi method was also used in developing a few national energy roadmaps and expert panel helped to obtain consensus and technology forecasting. We have witnessed use of quality function deployment (QFD) and innovation matrix in product technology roadmaps for electronics but in renewable energy sector we noted QFD used in one industry roadmap.

Analysis of renewable energy roadmaps also indicates that the TRM process has also evolved over time and it has become more systematic and robust. Roadmaps are developed after a series of workshops rather than depending on one or two workshops. Multiple committees are formulated to perform various tasks during the TRM process. Usually a facilitator guides the whole TRM

Table 6
Major differences between national and industry roadmaps.

National Roadmaps	Industry Roadmaps
Address multiple renewable energy technologies suitable for country	Focus on one sector or technology with an in-depth analysis
Give guidelines to the entire energy sector of the country	Identify future direction for a particular technology or industry
Energy security, high energy cost, global warming, environmental degradation, and enhancing national competitiveness are the main drivers for national roadmaps	Increasing energy cost, changing governmental policies, new business opportunities, desire to exploit new technologies and available resources are the main drivers for industry roadmaps
Strategies are mentioned at a broad level	Detailed strategies are formulated and action items are identified
Technical and commercial barriers are briefly mentioned	Detailed technical and market analysis is performed and key challenges & barriers are identified
There is not much focus on the supply chain issues	Supply chain issues related to the introduction /deployment of new technologies are also considered
Overall targets for energy generation from various sources/technologies are established	Detailed technology performance improvement targets and technology cost reduction milestones are established

process and keeps all participants focused. Moreover there is a growing tendency to use these above mentioned tools in the roadmapping process in order to help experts to better assess the technology and the market. Table 7 indicates use of various approaches and tools during the process of developing renewable technology roadmaps. Based on the study, usage of these approaches/tools is classified as high, medium, low and none for each type of renewable energy roadmaps.

4. Conclusion

As we have analyzed that the technology roadmaps have been extensively used in the renewable energy sector by developed countries for bringing a consensus among various stakeholders, creating a common vision, providing guidelines for policymakers and decision makers, establishing goals and targets, assessing promising technology alternatives, identifying markets, gaps and barriers, formulating strategies and action items to overcome all those barriers, and improving communication and coordination for technology development in order to increase contribution of renewable resources in future. Generally the vision, goals and targets in the roadmap provide guideline and direction. Identifying the present status of technology and market landscape is common in all roadmaps. However it is important to note that in some cases these roadmaps lack the broader product context as given in traditional product technology roadmaps due to evolving nature of renewable technologies.

We have noted that there are many similarities and differences in renewable technology roadmaps from each group. National roadmaps are issues oriented roadmaps and present high level broad strategies. At national level various energy issues and their consequences are discussed. Focus of national roadmaps is on energy security, policy formulation and environmental concerns. Industry roadmaps of renewable energy sector are usually emerging technology roadmaps. These roadmaps establish vision of industry, provide detailed guidelines for technology development and perform comprehensive risk assessment. However, there are many similarities and differences in national and industry roadmaps. Both types of roadmaps provide a framework for policy making and public–private collaboration. Moreover the process of making national and industry roadmaps facilitates networking among different players and stakeholders in that technology value chain. Organizational roadmaps have comparatively limited scope and these roadmaps are used for technology planning, aligning technical and business strategies, prioritizing projects and complying with changing energy policy regulations. Companies try to achieve their goals and objectives by better communication, coordination, planning, strategy, decision making and efficient resource allocation.

Analysis of approaches and tools used to develop renewable technology roadmaps tell us that workshops and meetings of experts are extensively conducted in the beginning of roadmapping process to ensure consensus and clarity of thinking. Scenario and SWOT analysis is also frequently used during the process of developing national and industry roadmaps. Delphi method and PEST analysis is used in a few cases of national and industry roadmaps.

Finally, as we have witnessed that both needs and technologies are evolving with time, therefore it is critical to regularly review and update the roadmaps. Our research doesn't indicate frequent revision of renewable technology roadmaps. It is important to establish roadmapping as an ongoing process rather than one time activity and roadmap should be a living document. Effective utilization of renewable energy technology roadmaps can contribute to the overall efforts towards creating a sustainable energy future.

4.1. Further research

Our analysis indicates that there are multiple approaches, methodologies and tools used to develop renewable technology roadmaps. During last decade there is significant worldwide increase in use of roadmaps for renewable energy sector. We also have seen several methodological improvements in development of different types of technology roadmaps [75–79].

It will be useful to make some efforts to standardize these renewable energy roadmaps by proposing a generic framework and

Table 7
Analysis of approaches and tools used in renewable technology roadmaps.

Approach/tool used	Type/level of roadmaps		
	National/regional	Sector/industry	Organizational
Scenario based planning	High	High	Low
SWOT analysis	Medium	Medium	Medium
Delphi	Low	None	None
Expert panels	High	Medium	Medium
Risk assessment	Low	Medium	None
PEST analysis	Low	Medium	None
Patent analysis	Low	Low	None
Citation network analysis	Low	Low	None
Internal corporate meetings	None	None	High
QFD	None	Low	None

Note:
i. Limited data is available for organizational roadmaps as compared with data available for national and sector roadmaps.
ii. High is used if technique is used very frequently in most of the roadmaps.
iii. Medium is used if technique is used in approximately 50% roadmaps.
iv. Low is used if technique is used in a few (one or two) roadmaps.
v. None is used if technique is not used.

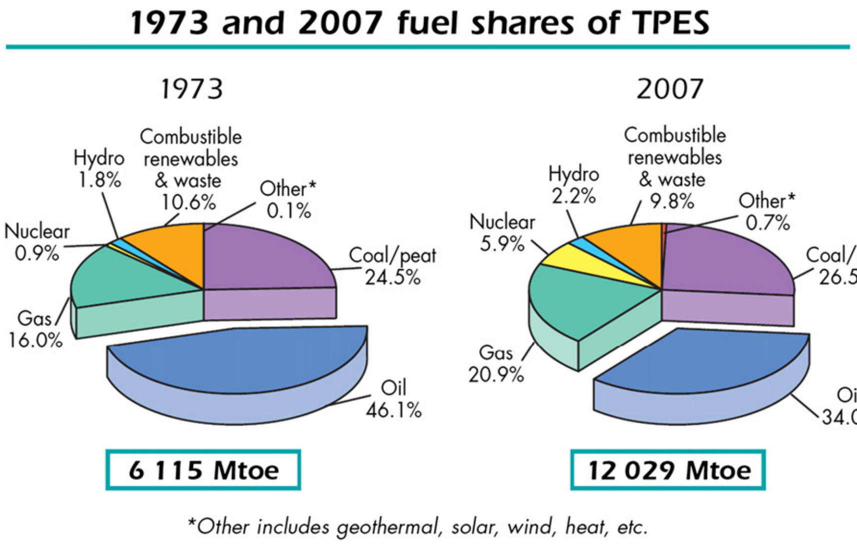
methodology suitable for making renewable energy roadmaps. Industry associations or any intergovernmental organization like IEA, EREC etc. can take the initiative and propose roadmapping guidelines for renewable energy sector.

It will be interesting to conduct some further research and investigate the practical usefulness of the technology roadmaps in renewable energy sector. Research can be conducted to investigate how closely the goals and targets are met and how roadmaps facilitate cooperation and collaboration for technology development.

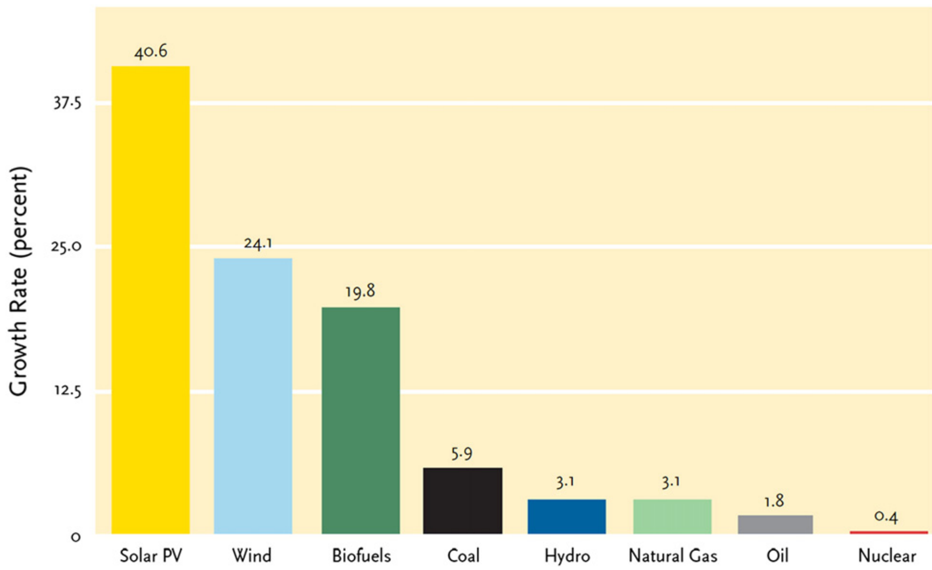
4.2. Research limitations

This research primarily provides a comprehensive overview of roadmaps developed for renewable energy sector. Roadmaps developed for other industries like semiconductor industry or aluminum industry are not analyzed. Descriptive data is presented in the form of tables and graphs followed by in-depth analysis. Statistical analysis is not performed in this article.

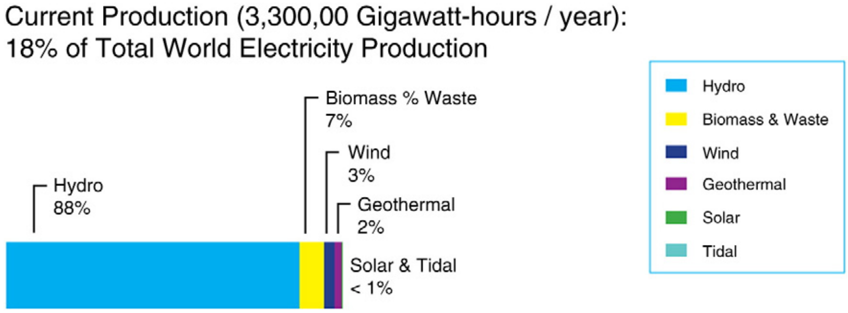
Appendix A



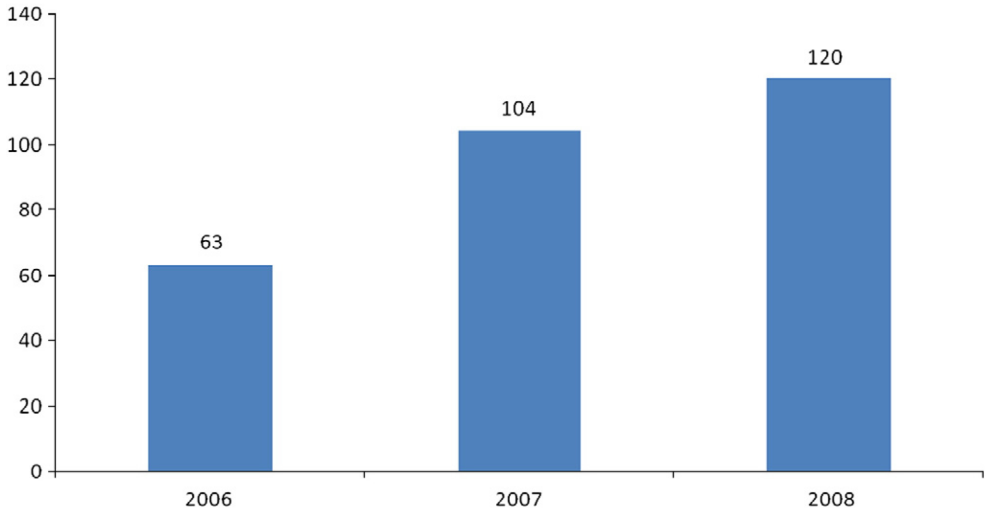
Worlds Total Primary Energy Supply (TPES) in 2007.



Average annual growth rate by energy source, 2002–07 [41].



Renewable energy production mix for electricity generation [71].



Global investment in new renewable capacity in billion USD [42].

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