Review of planning methodologies used for determination of optimal generation capacity mix: the cases of high shares of PV and wind

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Abstract: It is an undeniable fact that energy systems all over the world are at the point of a paradigm shift as a need for decarbonisation is eminent and unavoidable. The pressure to decarbonise mounts year after year. Since two thirds of all anthropogenic greenhouse-gas emissions come from the energy sector, decarbonisation is more about reducing emissions in the energy system than any other system in the world. The increased need for decarbonisation has resulted in the increased installation of photovoltaic (PV) and wind systems in countries such as China, India, Germany, Ireland, Denmark, Japan and USA. The increased use of intermittent renewable energy resources introduces a need for advanced methods of planning because traditional planning methods give sub-optimal generation capacity mix when the electric grid is faced with high shares of variable renewable energy resources such as PV and wind. In light of this, this review highlights the major changes in planning methodologies when solving for optimal penetration of generation capacity in systems with high shares of PV and wind. The major highlights are placed on why the methodologies need to evolve as penetration levels of PV and wind increase and further highlight missing issues from the current advanced methods.

1. Introduction

Energy systems in many countries around the world are moving towards decarbonised energy systems. This is a direct result of many developed countries having made bold emissions reduction targets to decarbonise their energy systems. European countries aim to reduce their GHGs to levels between 80% and 95% below 1990 GHG emission levels in the year 2050. In Paris, South Africa made some commitment to reduce emissions according to the peak plateau and decline emissions trajectory detailed in [1] if given financial support from developed countries. Peak, plateau and decline emissions trajectory means that South Africa is expected to peak its emissions between 2020 and 2030 at 398 – 614 $MtCO_{2eq}$ and stay constant for about 10 years and start to decline by 2040 until it reaches in the range of 212 – 428 $MtCO_{2eq}$ by 2050. Three quarters (75%) of GHGs emissions in South Africa comes from the energy sector. Within the South African energy sector, 55% of GHGs comes from electricity production [2]. Therefore it is evident that significant emission reductions will come from the electricity sector in South Africa.

This high level of GHG emissions from electricity production is based on the fact that 88% of South Africa's electricity is generated from coal-fired power stations [3]. Therefore for South Africa, decarbonisation is more about reduction of GHG emissions in the electricity sector. Decarbonised electricity systems will be characterized by increased penetration of renewable energy resources and findings in [4] articulate that this transformation (increased penetration of distributed renewable energy resources) is inevitable.

Research in [5] has shown that countries such as China, India, Germany, Ireland, Japan, Denmark and USA have high penetrations of wind turbines and PV systems within their electricity systems. For example, Germany has as high as 40% combined penetration shares of both PV and wind [6]. This increased penetration of PV and wind in these countries has resulted in reduced technology costs due to learning rates (economies of scale) [7]. The economy of scale is global in nature; therefore technological cost reduction experienced in European or Asian countries can be experienced in South Africa as well although at different scales. In 2011 when the first procurement of power from independent power producers (IPPs) started (called the Bid Window 1 – round 1 of procurement) in South Africa, the average cost of PV and wind was R3.66/kWh and R1.52/kWh respectively. In Bid Window 4, the average cost of PV and wind was at R0.86/kWh and R0.68/kWh respectively and has further gone done to R0.62/kWh for both of these technologies according to the latest procurement (the co called bid window 4.5) [8], [9].

Although the costs of PV cells and wind turbines are decreasing, the electricity they produce is heterogeneous in nature. Heterogeneity comes in three dimensions – electricity from all generators is not the same at any given time and location, electricity produced during peak times costs differently to base load electricity and electricity costs differently based on the bus to which it is connected.

Due to these three aspects that characterise electricity, no single technology can be said to be efficient over all the three heterogeneity aspects [10], [11]. That is why there have been three types of power plants that meet the electrical demand. The first class of these plants are called baseload power plants which produce baseload electricity and are mainly coal, nuclear and sometimes hydroelectric power plants in electrical systems in the world. The second class of power plants are classified as mid merit power plants and the examples are combined cycle gas turbines (CCGT), coal powered plants and the other class are power plants that provide peaking power and examples are open cycle gas turbines (OCGT) and pumped storage power plants.

With the advent of increasing installed capacity of intermittent renewable energy resources such as PV and wind, the need for baseload generation is reduced while the need for flexible power plants increases. Power plant is said to be flexible if it can easily ramp up and down as events and emergency situations arise in the electric grid system. The increased use of intermittent renewable energy resources brings with it operational challenges which the legacy systems (electric grids of the 20th century) have to adapt to. Emerging research has highlighted the need for planning methods due to these changes. The main contribution of this paper is to review how planning or modelling methodologies have changed over time with the transformation of the power systems.

The remaining sections of this paper will look into recent transformation of the electricity sector globally and the need for improved planning methods. Section 2 presents the methodological review process followed in conducting this paper review. Section 3 gives a detailed transformation of the global power sector, giving examples of both developed and developing countries. Section 4 presents a review of how modelling methodologies have evolved over the last 5 decades when the electrical systems were also transforming. This is a review of historical models and what has improved since development of first family of models. This section is followed by section 5 which analyses why there is a need for the improvement on these old modelling tools and methodologies. The section gives a detailed overview of what has motivated the need for the improvement and how the new improved method is used in solving for optimal capacity determination. Section 6 describes the modelling approach taken in most recent models that determined optimal generation capacity. Section 7 discusses the challenges and limitations encountered by long term planning models. Section 8 discusses implications of issues presented in Sections 3, 4, 5 and 6 gives some suggestions of how the current methodologies can be advanced further when seeking optimal penetration of PV and wind.

2. Methodology used to conduct the review

This review follows a systematic process as proposed by [12]. The methodology adopted in this review follows the process as shown in Fig. 1. The process starts with the definition of objective of the review. The main objective of this review is to highlight existing planning methodologies and highlighting evolution of these methodologies which comes as a result of transitions occurring in the energy system. To conduct the review, extensive literature review was needed and during the literature review process, it then became obvious that a number of changes are occurring in the electricity planning and the current status is such that the work is done separately between the three spheres (generation, transmission and distribution) of the electricity system. The review gives a highlight of missing links between planning that occurs at transmission and distribution with the generation plan (integrated resource plan). In the process of highlighting the evolutions, the review finally highlights improvements that still need to be done to these models and finally give suggestions of how current models/tools can be used to account for some issues that have risen to be of critical nature.

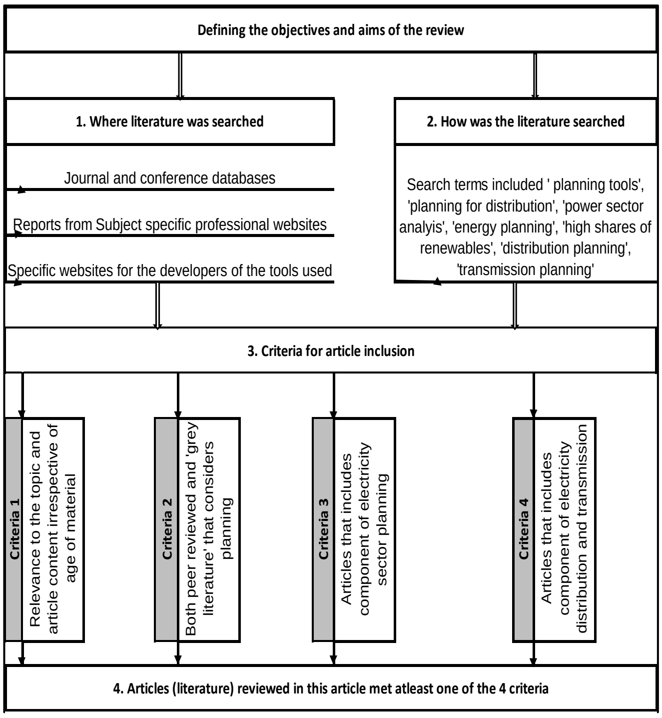

Fig. 1 *Systematic review process followed in this work*

3. Power sector transformation: a brief overview

The power sector is transforming at an alarming rate due to increased rate of installing intermittent renewable energy resources such as wind and PV. Increasing installations of PV and wind renewable energy resources are a direct result of global learning that has filtered into several developing and developed countries alike [13] - [16]. The bold GHGs emissions targets made by the European Union in 2009, China, USA, India, South Africa and other developing countries, accompanied by the signing of the United Nations Framework Climate Convention’s (UNFCC) Paris climate agreement by most countries, favourable feed-in-tariffs [17] resulted in massive investments made in PV and wind [11], [16], [18] - [29]. Besides reducing costs, PV has also developed to levels where the efficiency of PV modules is reported to be as high as 23% and 26% [30].

As seen in Fig. 2, globally China is leading in terms of the size of installed capacity of wind and PV, followed by the USA and Germany. China has installed capacity of 168 GW and 77 GW of wind and PV respectively as of 2016 [24], [27]. The USA has installed capacity of 82 GW and 40 GW of wind and PV respectively [21], [24]. The leading European country (Germany) has installed capacity of 41 GW and 50 GW for PV and wind respectively (see Fig. 2) as of December 2016 [12]. After emission targets were made, Germany made some specific policy (Germany’s Renewable Energy Act) which favoured inclusion of renewables into their electric grid [7], [12].

Despite Denmark having the smallest installed capacity as shown in Fig. 2, a high proportion of energy in Denmark can be met by wind and PV. According to [28], 39% of energy came from wind in Denmark in 2014. This results in Denmark having the highest share of energy provided by wind and PV in the world. This is because Denmark has installed capacities of 5 GW and 1 GW for wind and PV respectively, its peak demand is 6 GW and Germany's peak demand is 80 GW. In comparison to Germany, only 18% and 8% of energy was met by wind and PV respectively [18]. Fig. 3 presents, installed capacities of wind and PV relative to their electric system size (peak demand) and it clearly shows that Denmark is out performing all other countries. Despite China and USA having installed more capacity of wind and PV, in relative (relative to the size of their system) terms, their capacity is very small as depicted in Fig. 3.

One other important aspect that is introduced in markets with high shares of variable renewable energy resources is the economic value of the electricity produced by these resources. Economic value is impacted by heterogeneity of electricity discussed above. Several studies have already shown that optimal penetration of wind and PV should take its economic value in consideration [31], [32]. The value of electricity in economic terms means that electricity produced by PV during the day does not add the same economic value when compared to the electricity produced by wind and other technologies during the evening peaks when electricity produced during these periods is costly. Unless the load shape changes to match power production from these variable resources, increasing PV and wind beyond a particular penetration level lowers the value of renewables. At low penetration levels, the value of electricity produced by wind and PV is higher than the average electricity price. But, as penetration levels increase, the value starts to decrease due to increase in integration costs and increased generation curtailments from these resources. Research in [30] - [33] has pointed out that, once variable renewable energy resources exceed 30% to 40% within a system, the electricity generated from these resources costs higher. Although the economic value decreases the average cost of electricity but decrease in cost is not at the same scale. Therefore, optimal penetration of intermittent renewable resources must be assessed using the value of electricity together with the cost (average system electricity cost from all technologies) for a fair assessment of optimal penetration.

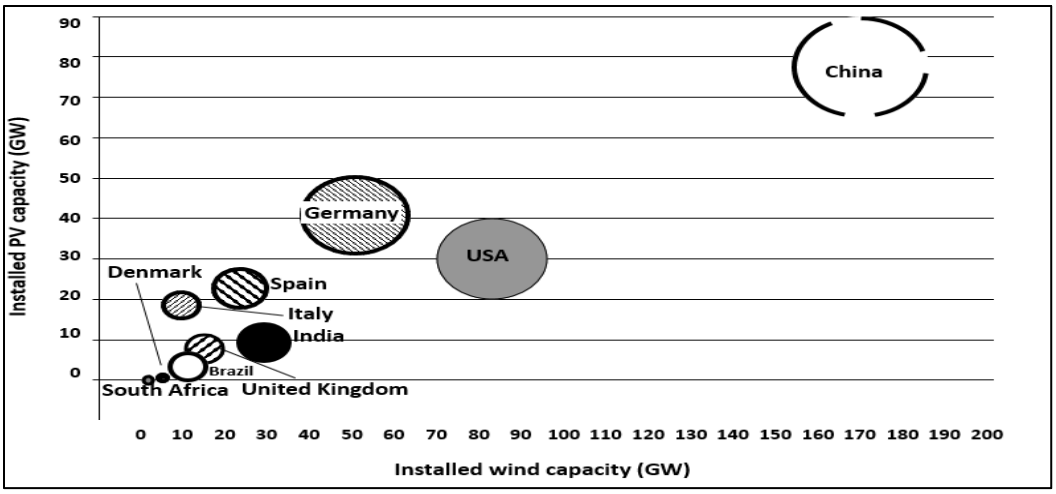

Fig. 2 *Installed wind and PV capacity in some selected countries [16] - [23]*

The variability of the PV and wind does not only necessitate additional flexibility resources as mentioned before, but also have some undesired feedback at high penetration levels due to increased integration costs. Unless the economic value of these intermittent resources is increased or kept constant, caution is required in adopting increased penetration of wind and PV. The value of wind and PV can be kept constant if electricity storage is added to the mix but currently large scale storage is still not economic hence several countries find it easier to deal with decreasing value of electricity from wind and PV. Curtailments are required because electricity generated by PV and wind is dispatched based on the weather conditions (when the sun is shining and when the wind is blowing) and the production might occur at the time when electricity demand is very low.

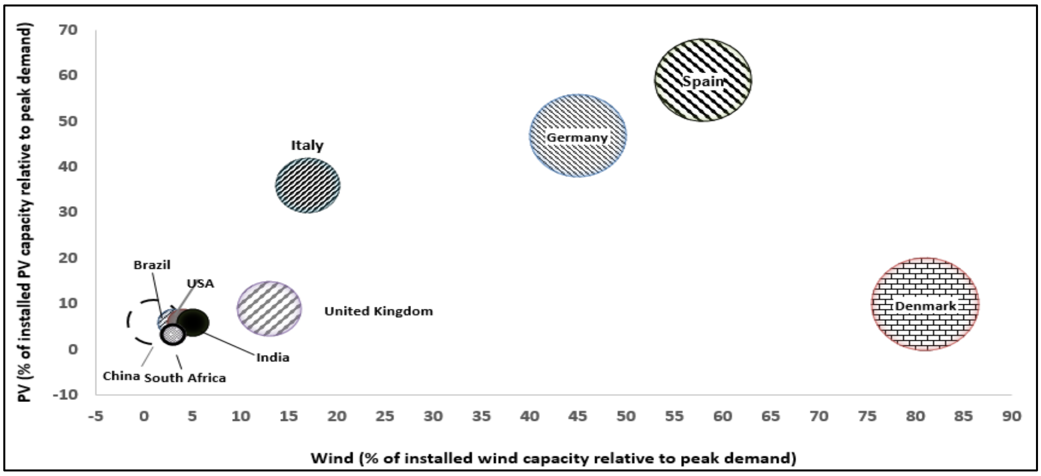

Fig. 3 *Installed wind and PV capacity relative to the size of the system [9], [16] – [19], [24] – [29]*

Improved resource modelling has shown that the technical resource potential of wind and PV is sufficient in many countries (e.g. Germany, South Africa, Zambia, etc.) [33] - [42]. Although technical potential and costs reduction are beneficial for these technologies to find prominence in the system. Research has shown that there is an optimal deployment level for both wind and PV given their variability and uncertainty [10], [11], [33], [35]. In systems with low levels of penetration of these intermittent resources, their grid effects are negligible. At high penetration levels, plethora of research has demonstrated that these two technologies pose challenges to the operation of the power grid due to their intermittency and variability [28], [30], [43 - [52].

For non-interconnected systems (such as African systems with weak transmission links between countries), the operational challenges are three fold when capacities of these two resources are high in the mix of generating technologies:

1. Wind and PV variability (varying every hour and minute due to weather events) introduces steep ramps which require flexible generation that can ramp up and down quickly. According to research variability introduces what is called profile costs which are significant portion of integration costs [10], [11], [30] - [32].
2. The intermittency makes the output from wind and to a less extends PV uncertain [46]. Recent developments have demonstrated that short term forecasting of wind and PV helps system operators to know day ahead how wind and PV will behave hence appropriate resources (reserve) can be made available for dispatch ahead of time [33] - [39].
3. Given the operational characteristics of variable energy resources, there are power quality and voltage stability issues as identified in [48] - [51] that needs to be assessed, controlled, observed and mitigated appropriately [49]. Therefore planning for a system with high shares of intermittent renewable energy resources has to take into consideration the needs introduced by these resources in the power system. As a result, transitioning to system with high shares on decentralized distributed renewable generation requires observability [49] and controllability from the operators' point of view. This function can be achieved by use of information and communication technology (ICT).

The impacts brought by these three aspects (variability, intermittency and grid stability issues) necessitate a paradigm shift in long term planning methods that assess the impact of increased penetration of PV and wind, more especially on the grid operation. The most critical aspects that require consideration in the new planning methods are assessment of operational flexibility resources [38], [53] - [58], which are a necessity for proper operation of the grid with high shares of variable renewable energy resources such as wind and PV. Another important aspect is finding a way of costing operational flexibility as a resource in long term planning studies. The third aspect is the inclusion of additional costs such as smart grid components (ICT infrastructure) that will be introduced more especially at distribution level due to increased penetration of variable energy resources.

Besides planning for variability or intermittency, flexibility needs, research in [59] shows that new protection methods are needed to deal with bi-directional flow of power from distributed PV systems. In systems that are not electrified, the most prominent type of planning is for mini-grid systems [60], which look at economic parameter, resource planning, reliability issues and resource planning under uncertain environments [61], all at the same time. Mini-grid planning presents an interesting way of planning which should be incorporated in grid connected systems. When planning for mini-grid, generation and distribution planning are lumped together hence a composite system is produced an in a way that there are no hidden costs.

4. Review of energy planning methodologies and need for their evolution

Energy modelling is the art that was introduced in the sixties and its importance intensified in the seventies due to the oil crisis that hit the world in 1973 [62]. In the early 1960's the concentration of models was on the demand and supply of a single energy source such as oil or coal [63]. As criticism of these models increased, a new family of models were developed in the 1970's. The 70's saw an increase in number of optimisation models that still maintain the fundamental property of balancing demand supply at system level [62], [63].

These first families of optimisation tools/models looked into the entire energy system using the reference energy system which analyses the flow of energy from primary resources to final end use [64]. The first models are energy flow optimisation model (EFOM) and market allocation (MARKAL), now called 'The integrated MARKAL_EFOM System' (TIMES) and Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), Wien Automatic System Planning Package (WASP), National Energy Modelling System (NEMS) [65]. These models primarily focus on modelling the deployment of large centralised, dispatchable thermal generating units which are fuelled by coal, natural gas, and uranium [44]. Recent reviews of energy models in [64] - [68] show that a plethora of these energy models exist (both open source and commercial).

With the transformation of the electric sector, there has been an increase in the development of models that analyse several aspects of electric energy system (capacity determination, market operation and policy implications). These models are the European Electricity Market Model (EMMA) [13], [30], [33], python for power system analysis (PyPSA) [66], Switch [69], PLEXOS [70], [71], Power Agent-based Computational Economics (POWERACE), Price-Induced Market Equilibrium System (PRIME) [63] and many others found in [67], [72], [73]. The resurgence in only electricity models is brought up by the fact that the electricity sector is experiencing massive transformation as highlighted in Section 3 and a need for improved methods has increased. Despite the difference in model architecture, the aim of electricity expansion models is always to find optimal mix of capacity from different technologies. Although models solve for differing objectives, priorities and level of detail [44], the fundamental framework in all of them is that energy demand must always be equal to energy supply (energy must balance).

4.1. Increased need for temporal resolution

Historically and traditionally, system planning models assess the optimal deployment of generation technologies by looking at the cost of generating technologies by using a so-called screening curve methodology and adding some constraints such as greenhouse gas (GHG) emissions as is done in [74] - [80]. The screening curve methodology takes a load duration curve (ordered annual load) and fills the area under the curve with technologies that will result in least cost electricity system [65], [73]. Screening curve is the first order capacity approximation technique and the time resolution is usually annually and to increase the resolution, time slices are used to split the annual duration load into time blocks.

For a typical system as show in Fig. 4 (taken from [81]), pumped hydro storage and open cycle gas turbine (OCGT) can be used to meet the peak demand while the combined cycle gas turbine (CCGT), hydro and pumped storage meet the mid-merit load while the base load is met with hydro only.

By looking at technologies that are able to meet a given load while minimizing the overall system cost (overnight cost, fixed and variable costs for a given period of one year), these models give optimal capacity options. The temporal details in these models are usually very low [76]. The annual load in Fig. 4 is usually split into time slices and the model solves for capacity in those differing time slices. The higher number of time slices, increases the computation requirements. In [68], [77], 260 time slices were used and using the same modelling tool, Despres et al. in [63] used 17 time slices, and in [29], 32 time slices were used. In [74], the time slices might be lower because the modelling was done at a regional level and not for a country. For a particular case of South African, the Energy Research Centre at the University of Cape Town case uses 20 time slices for splitting the annual demand [78, 79]. Recent work has shown that low temporal resolution gives sub-optimal capacity determination when dealing with variable and intermittent renewable energy resources [33, 66, 81 - 91].

The example shown in Fig. 4 does not consider the chronology of the load when solving for the least cost system. In legacy systems (where conventional power plants operate), this chronology did not matter as the source of variability was only the load. As variable renewable energy resources are added to the system, research has demonstrated that there is a need to capture this chronology [58, 87, 90, 92 - 95] due to the changes in the way the electric system operates. The fact that electricity generation from wind and PV is dispatched by weather and not necessarily by the control centre, the load duration curve, shown in Fig. 5 is altered with increased penetration of intermittent resources. Load duration curves in Fig. 4 will result in residual load duration curves shown in Fig. 5 at different PV penetration levels. The conventional power plants will be meeting a reduced peak load, which translates to differing dispatch regime in comparison to the dispatch for load in Fig. 5. In this instance, pumped storage and OCGT (peaking plants) will be used to meet a reduced energy demand (area under the curves) compared to the load in Fig. 4.

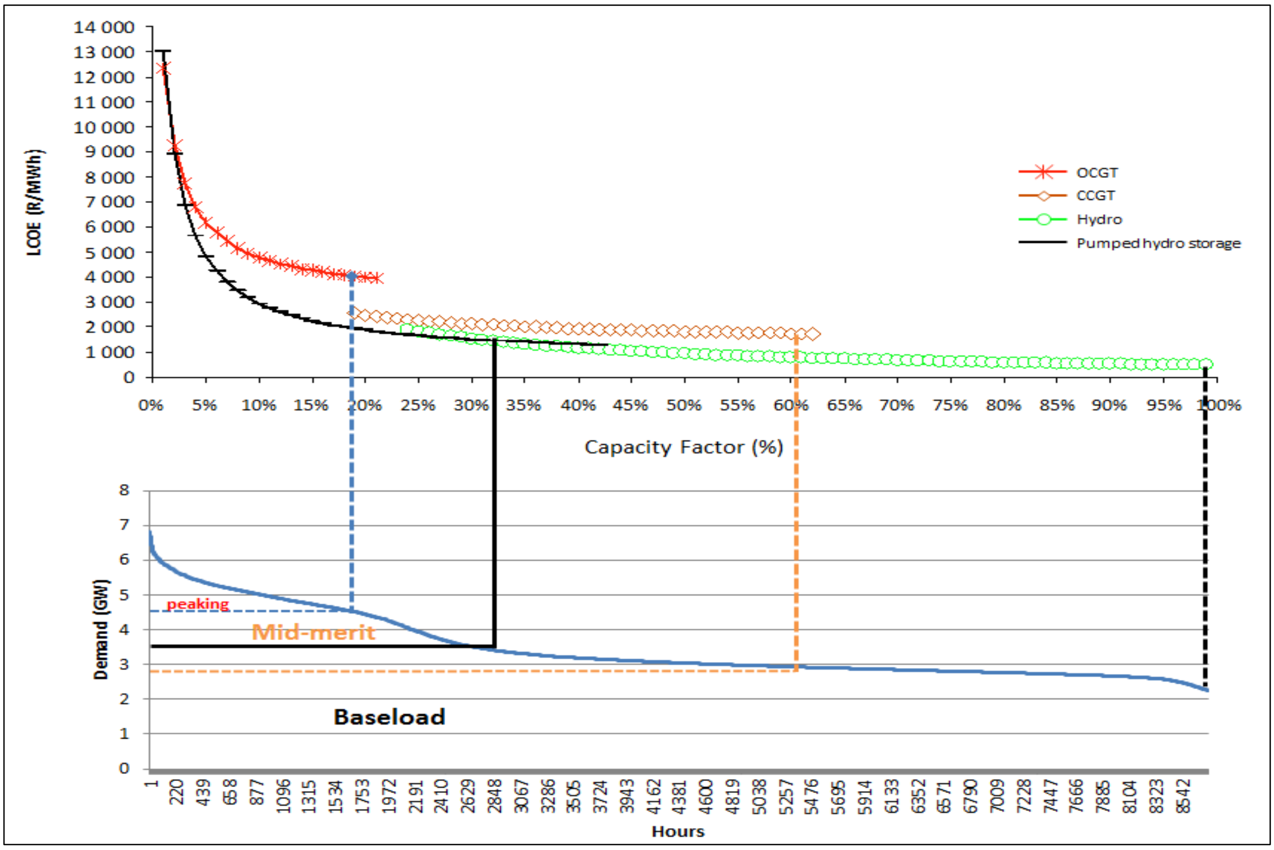

Fig. 4 *Load duration curve and screening curves*

Power system planners, no longer plan for the system load, but they must plan for net load (system load minus generation from wind and PV). Given the time when the variable generation happens, net load characteristic can determine whether the use of the peaking power plants or mid–merit power plants will be reduced. The PV reduces the peak load in Fig. 5. Therefore low temporal resolution is critical when running the long term planning studies because it takes into account the economic/market value of electricity produced by variable renewable energy resources. Exclusion of low temporal resolution does not take the market value of electricity from PV and wind resources and this is demonstrated in [96]. Using low temporal resolution has a potential to both over-value and undervalue a variable renewable energy resource depending on the parameters used [96].

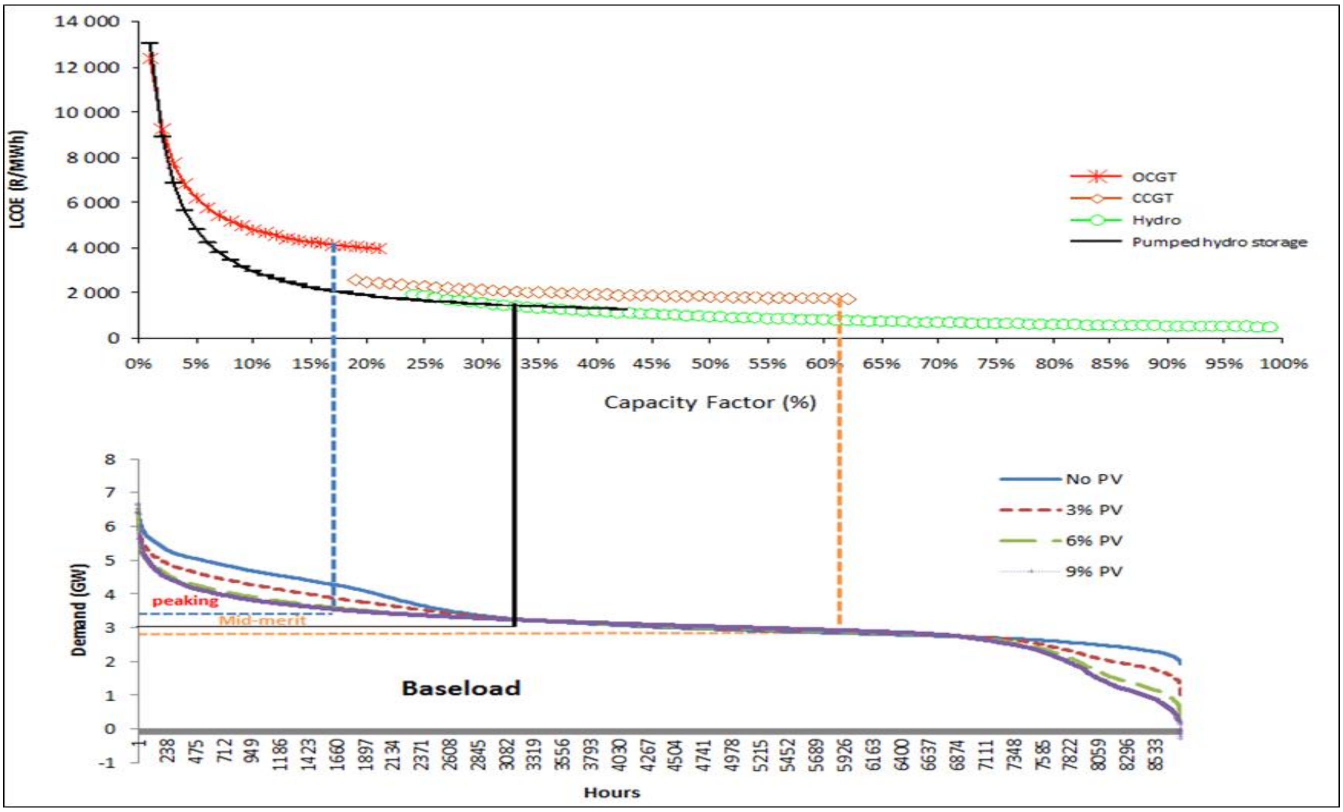

Fig. 5 *Net load after introduction of PV in a typical commercial, Adapted from [82]*

4.2. Increased need for flexibility assessment

Increasing the use of intermittent and variable renewable energy resources does not only increase the need for temporal resolution in models (including chronology of the demand), it also increases the need for flexible electricity grid [97]. The new planning methods must incorporate the assessment of flexibility requirements for electric systems with increased variable generation [98]. Increasing the penetration of variable renewable energy resources necessitates more flexibility into conventional electric systems. Flexibility is required because wind and PV increase the magnitude of variability in the net load (residual load) as demonstrated in Figures 4 and 5. A Flexible generation or responsive demand is needed to deal with this variability more especially when wind and PV are massive in the grid [38, 93]. Műller in [56] argues that inclusion of flexibility in long term planning studies is limited. Ignoring the inclusion of flexibility in expansion modelling results in expensive capacity plans as demonstrated in [43, 57, 58, 82, 99-103].

Different researchers have looked at the flexibility using different flexibility metrics [31, 58,103]. In [57], system flexibility can also be measured using percentage of installed generation type to its peak demand. Using system capacity and peak ignores other dimensions of the flexibility which are not capacity related. Therefore a more comprehensive measure must be developed. In [43, 54], net load ramp rate is used to measure the flexibility requirements and in [95], it is argued that ramp duration is also an important metric for system flexibility. In [54], it is argued that flexibility can be assessed in 3 ways – ramp rate (MW/min), capacity provision (MW) and in energy provision (MWh) and ramp duration can be ignored since it is a function of ramp rate.

Ramp rate is calculated by subtracting the previous hour's net load from the current hour as shown in Eqn. (1), where t is time in hours.

$$Ramp\ Rate\ = Net\ Load\ (t) - Net\ Load\ (t-1) \tag{1}$$

The ramp factor is determined using Eqn. (2). Ramp factor of 20% means that the generation fleet must increase its output by 20% in the next hour [95].

$$Ramp\ factor\ = \frac{Ramp\ Rate\ (t)}{Net\ Load\ (t-1)} \tag{2}$$

Ramp requirements tell the system operator the megawatt per hour that is needed from the generation fleet. Plethora of modelling studies such as the one done in [11, 43, 57, 58], 83, 99 - 103], deal with flexibility by assessing the metrics in Eqns. (1) and (2) and most of the analysis in these studies is done after optimizing for capacity expansion. The main aim of these models is to check system adequacy (flexibility requirements for short to medium term) following capacity determination. Trying to determine capacity for longer periods (20-30 years in the future) on an hour to hour operational schedule of the power system is computationally expensive and in [11], a two stage iterative process is adopted. A two stage iterative approach means that in the first iteration, optimal capacity is determined using a certain temporal resolution (may be 100 time slices). At the second stage, a short term modelling tests for system adequacy and flexibility. If the flexibility requirements are not met, the temporal resolution of the long term model is increased. Then the second stage iteration follows to test system for adequacy and flexibility again until the requirements are met.

Determining optimal capacity with low temporal resolutions does not incorporate flexibility assessment [93]. According to [87], planning for flexibility must deal with aspects of frequency control: economic re-dispatch of units every 5 minutes (load following) and automatic generation control (regulation). Bebic [93] asserts proper flexibility assessment is done at time scale of load following. If one does not analyse the operational flexibility at this level, operational aspects of the power system are ignored. The challenge with this approach is that 5 minutes load and generation data will be required and majority of utilities do not measure data at that time scale [16].

To avoid the heavy burden on computation, Palmintier [99] used clustering methods to lower computational needs required for running a capacity planning model for 8760 h in a year for the entire planning horizon. Power plants were clustered according to their common functionality in the grid. In this way the residual ramp magnitudes and rates are dealt with during capacity determination and it is the better way of dealing with flexibility.

4.3. Increased need for voltage stability and frequency control studies

With increased penetration of intermittent renewable energy resources, there has been an increase in studies that look at voltage stability and frequency issues. These studies are highlighted in [39, 96 - 102]. Voltage stability and frequency control studies assesses the voltage behaviour and the frequency control requirements [102]. Frequency and voltage control studies fall in a different domain of planning to that of expansion planning which seeks to do power balancing in an economical manner.

Capacity expansion planning studies mostly ignore the voltage and frequency technical operations of the power system and try to balance demand and supply at all times [76, 77, 80, 103 - 108]. The stability studies presented in [109 - 113], deal with the frequency and voltage control operations of the grid which look at power balance property, as well as safety of the equipment in the interconnected power grid. Increasing non-synchronous generators into the electric system alters the system altogether. The inertia of the system – which is maintained by rotating masses of the conventional thermal turbines in the grid, cannot be provided by PV. Although some research has suggested the use of virtual inertia [114] through the use of flywheels, wind turbine control and batteries, increasing the penetration of PV means that inertia provision becomes a critical resource that must be provided for. Few studies have tried including power stability issues in long term planning studies. This type of analysis was done in [115]. By including the reliability (inertia issue) in the long term planning, it was shown in [115] that reliability decreases with high penetration of intermittent renewable energy resources, which then jeopardises the system stability. The strong message from this single study is that inertia and other issues related to system stability play an importance role in long term capacity plans which consider variable renewable energy resources.

The increased need for inertia in the grid explains why there is an increase of voltage stability and frequency control studies. Although it is currently not clear how these operating conditions can be added in the long-term planning studies, their exclusion may compromise the operation of the system that was designed to have inertia. Electric system with high shares of PV will have to procure inertia resource at an additional cost [116]. Therefore, it is crucial to cost inertia services in long term planning, more especially if the systems will have increased installation of PV. Even though no single model has been developed that can assess power stability issues in conjunction with power capacity expansion studies, atleast costing of this resource must be accounted for in power expansion models.

The other critical issue that needs to be considered in systems with high shares of wind is planning for reactive power as demonstrated in [117]. This involves sizing capacity and putting such a capacity at optimal location to maintain smooth operation of the grid [118].

5. Accounting for costs throughout the entire electricity chain

5.1. Increased need for voltage stability and frequency control studies

Traditionally, planning for the electricity system is done separately for electricity generation expansion planning, transmission and distribution network expansion planning [119, 120]. Transmission and distribution planning studies always follow the electricity capacity expansion planning studies. There are at least two main reasons why this separation of the planning processes is practiced. Firstly, it is done this way so that the transporting assets (transmission and distribution networks) can follow generating assets wherever they may be installed. According to research in [120], the reason for this practice in the 70's was because investments into generation expansion were far more expensive than building transmission and distribution lines. Although there is a rapid transformation in the energy sector, this separation has been the case even recently is some systems in the world as well as in South Africa. The second reason emanates from the fact that the planning tools used in these three spheres are complex (see distribution modelling inputs in [119]) and the details cannot all be incorporated in one modelling tool. This will not be good because the aim of models is to abstract reality by capturing important parameters of the system without complicating the model; else the model is rendered useless.

Future systems will be highly decentralised [4] and this means that the cost of the energy system will also increase at transmission and distribution levels. In current systems, the cost of generation is still high and the cost of transmission is assumed to range between 4 - 5% to the cost of generation for wind generators [119]. Work in [120], [121] proposes inclusion of transmission and generation co-optimisation. This co-optimisation of generation with transmission planning was carried out in [122].

By having distributed generation dispersed over a large area will increase the network cost at distribution level. Other researchers point out that cost of distribution will be very high due to increased need for visibility and controllability [123], but thus far no research work has tried to incorporate distribution system planning in long term planning. Given these cost drivers and cost savings as demonstrated in [47, 124 – 126] long term modelling studies must find a way of incorporating distribution issues in their plans.

The third reason for exclusion of distribution and transmission grids in long term planning is that all technologies will increase integration costs. For the centralised system, these are mainly grid related costs [40] and contingency reserve costs [127]. While this is true that every technology induces some integration costs, the variability of PV and wind introduces additional costs called profile costs and intermittency introduces another type of cost called the balancing costs on top of grid costs. Therefore with PV and wind, there are grid related costs plus profile and balancing costs which are all called integration costs.

5.2. Integration costs induced by variability of PV and wind

Due to increasing integration and investment costs and given the fact that electricity is a heterogeneous good and its economic value is dependent on when it is produced. Some researchers in [33, 128] discovered that PV and wind can increase up to an optimal penetration point. Exceeding this optimal point, the value of electricity supplied by these resources decrease further and the cost of electricity will continue to rise due to increase in investment and operating costs. Therefore when planning for a system with high shares of intermittent renewable energy resources, it is crucial to include the value of PV or wind in the analysis.

Once these intermittent (variable and uncertain) renewable energy resources exceed a particular level, the existing technology mix of generating units must adapt to the new operational situation. Some other mid-merit and base load plants may have to operate at sub-optimal production levels. They operate at sub-optimal levels because their generation has to be curtailed so that the generation from renewable energy can be accommodated or generation from PV and wind can be curtailed.

6. Review of studies using improved planning methods

Recent electricity modelling efforts have assessed the possible capacity optimal penetration of variable renewable energy resources in various countries and regions [11, 26, 32, 43, 49, 87, 89, 128 - 132]. An overview of current studies presented in Table 1 shows that the resolution of recent models at 1 hour resolution which has changed from time slice concepts used in earlier planning tools. Although some studies in [43, 54, 57, 58] have proposed inclusion of flexibility assessment when optimising for long term plans, very few studies have actually implemented flexibility assessment in their planning as shown in Table 1. Amongst the reviewed studies, only two studies have included both generation and transmission co-optimisation and none have included issues at the distribution level [119], [148]. Among the reviewed studies only one planning study considered power stability issues [116]. Given the required need to incorporate flexibility, grid stability, low temporal resolution and inclusion of the entire electric grid value chain, in planning for long term plans, it is clear that very few planning studies have considered these important aspects. Therefore, there is a need for further development of models or researchers must find a way of costing all these important aspects of the grid.

Studies that have used long term models such as TIMES with low resolution and linking it with other optimal dispatch electricity models do not necessarily optimise the system with high temporal resolution. What these studies are doing is testing the adequacy of the existing plan that is already determined by high resolution models. These types of studies are found in [58, 149 - 158]. Following generation expansion plan and unit commitment analyses, then power system stability issues are analysed and studies as done in [48, 50, 110, 159-168], must be performed.

Table 1 Comparison of aspects considered in long term planning methodologies considering increased variable renewable energy resources

Tool used	Country/Region	Temporal resolution	Flexibility requirements	Transmission considerations	Power stability considerations	Distribution considerations	Study
EnergyPLAN	Indonesia and Thailand	1 h	No	No	No	No	[108]
	Hungary	1 h	No	No	No	No	[132]
	Macedonia	1 h	No	No	No	No	[133]
	Denmark	1 h	No	No	No	No	[134]
	China	1 h	No	No	No	No	[135]
	Croatia	1 h	No	No	No	No	[136]
	Island of Mljet, Croatia	1 h	No	No	No	No	[137,138]
	Frederikshavn, Denmark	1 h	No	No	No	No	[139]
	Aalborg	1 h	No	No	No	No	[140]
	Jordanian	1 h	No	No	No	No	[141]
TIMES	France	1 h	Yes	No	No	No	[87]
TIMES	Re-union Island	1 h	No	No	Yes	No	[116]
TIMES and EnergyPLAN	Norway	five periods per week [TIMES], and 1 h for [EnergyPLAN]	No	No	No	No	[74]
TIMES, OSeMOSYS and PLEXOS	Irish	Annual and hourly	Yes	No	No	No	[58]
Unit commitment Energy Dispatch (UCED)	Non- specific	15 min - 1 h	Yes	Yes	No	No	[119]
Heat, Hydrogen and Renewable Energy System (H_2RES)	Porto Santo Island	1 h	No	No	No	No	[141]
	Island of Sao Vicente, Cape Verde	1 h	No	No	No	No	[142]
	Portugal	1 h	No	No	No	No	[143]
Long-range Energy Alternatives Planning System (LEAP)	Ghana	Annual	No	No	No	No	[144, 145]
Mesap_PlaNet REMix	Canary Islands	1 h	No	Yes	No	No	[141]
Authors' own algorithm used	Belgium	1 h	Yes	No	No	No	[58]
Authors tool developed with Python	Australia	1 h	No	No	No	No	[146]
Authors own modelling tool	Japan	10 min	No	No	No	No	[147]
General Algebraic Modelling System (GAMS)	Texas, USA	1 h	Yes	No	No	No	[99]

6.1. Inclusion of distribution system costs in long term planning

The time for treating distribution systems as passive transportation systems is over. Distribution systems are increasingly becoming connection point for PV systems [7, 167], therefore any planning that ignores distribution issues does not take reality into account. Ignoring issues at distribution makes generation planners to either over-estimate the load and/or also under-estimate the system wide cost impacts. Despite the changing energy paradigm, there is limited or no inclusion of events occurring at distribution level when conducting long-term electricity expansion studies as shown in Table 1.

Inclusion of distribution systems in long term planning studies can help in having an optimal system [55]. Planning for these distributed units will help municipalities especially in South Africa to understand the impacts of distributed generators on the entire electricity value chain and can help them to understand the impacts on their revenue. Having this understanding is crucial so that municipalities can find ways of restructuring their tariffs and also finding new other services that they can offer to their customers. Within the South African municipalities, lack of this needed perspective makes many municipalities to block connection of distributed generators on their network. The aftermath of this is illegal connections, where people just connect because PV is becoming economic at very fast rate [9].

In [10], [11], Hirth et al. suggest inclusion of integration costs when accounting for optimal penetration of PV and wind. After including these integration costs, the new system cost is called the system levelised cost of electricity (LCOE). The integration costs are grid related costs, balancing costs and profile costs. In most instances grid costs are the transmission expansion costs. As Jairaj et al. [4] articulates that the future electric grid will be highly decentralised, significant changes are required at distribution level to integrate variable renewable energy resources. There will be some costs associated with these changes and in [132], it is observed that the increased costs will be due to information and communication infrastructure (ICT) that will be needed for observability and controllability.

Although strengthening the distribution grid is critical, it is also important to look at other parallel costs that will be added to the system due to the increase of distributed and intermittent renewable energy resources in the electric system. The other parallel costs that need to be considered at distribution level are the ICT investment costs and operational costs. In [132], ICT can be used for power generation management and control-related integration of power management. This is a great concern because it is discovered in [132] that ICT infrastructure costs can increase the distribution network costs by 40%.

7. Challenges and limitations of planning methodologies used for optimal determination of optimal generation

As with planning for any system, there are challenges and limitations encountered when planning for capacity determination. Input parameters such as demand, cost assumptions together with assumed discount rates, may deviate far away from what the plan has assumed. Therefore, the critical and most challenging issue around these methodologies is dealing with uncertainties around inputs. With respect to demand, the critical issue, is the demand forecast which is at the heart of the generation plan.

In expansion capacity models, the objective is to plan for the magnitude of the load not when the load is occurring [169]. Given the importance of when electricity is generated, new methods must find ways of planning for load taking into consideration when it is occurring, as the load and the time it occurs determines the economic value of meeting the load. With new ways of planning the aim is to concentrate on the net load. The optimisation optimises for the residual load as discussed in Section 4.1. The challenge with this is conducting a demand forecast of the net/residual load as both PV and wind resources cannot be predicted with some accuracy, given the uncertainty of climate related forecasts.

For systems with high/increasing share of variable resources such as PV and wind, the intermittency of these resources must be incorporated into the plan. One way of dealing with that is making the demand to respond to changes in the supply by adjusting what the demand can handle (adapting to supply side variability) while the other way is to reduce peak load. Research in [169, 170] suggest the use of demand response (DR) to co-optimise both supply and demand side.

Although this appears to be an innovative way of integrating supply side issues and demand side issues, the limitations that these have are serious and compromises the answer the co-optimisation gives.

1. This co-optimization assumes supply curves of demand side management (DSM). This presents a serious problem because DR programs are used by utilities for planning, operational and reliability purposes different from supply-side resources. DR programs are usually subject to rules which can limit the number of hours and capacity they can contribute in a year [171]. Modelling does not usually take these issues into consideration, hence it can result in over estimating the role DR can play in balancing supply and demand.
2. The characterization and dispatch of the demand response is not clear in most integrated resource plans that claim to include DR.
3. The results for different demand response portfolios are present values over the entire period of the analysis instead of an annual basis

8. Discussion

For future modelling of the power sector, it is important to consider issues (power stability, power quality, protection issues etc) encountered at transmission, distribution and generation. Inclusion of these issues is necessitated by the changing operation of the electric grid system. Even if the physical characteristics cannot be included, atleast there must be a way of incorporating the cost of taking care of these issues in long term plans. By adding integration costs together with investment cost, studies in [9] termed this new cost metric the system levelised cost of intermittent and variable energy resources (system LCOE). Besides the system LCOE due to integration costs (profile costs, balancing costs and grid related), it is critical for future planning studies to assess the costs of parallel infrastructure such as ICT infrastructure and inertia services.

This is needed because ICT brings the benefit of observability and controllability (smartness) into the grid which is a critical operating condition when having many distributed generators that are variable and intermittent in nature and are spread over a wide range of locations [159]. Carpinelli et, al. in [159], stress that PV systems need coordinated voltage control to alleviate the over-voltage introduced by PV but to implement a coordinated voltage control needs reliable communication infrastructure which is a very costly solution. These cost drivers must be included in the analysis just like emissions costs and water costs for coal based systems.

The inclusion of all these aspects that affect the cost of the electricity system as suggested here is not new to the electricity generation planning. With recent developments for decarbonisation, electricity planning models now as in [9, 84, 99] include the cost of carbon in models because fossil fuels pay the penalty for emitting carbon.

To plan for future electrical system, new improved methods must be adopted. All of the existing models do not have the capability to consider all the impacts that variable renewable energy resources (such as PV and wind) bring to the electricity system. In the absence of a current supermodel that can consider all the issues that are raised holistically, it is suggested that both bottom - up and top - down approaches are used to model future electricity systems.

9. Conclusion

The linkage between bottom-up and top-down planning will offer insights along all the electricity value chain. These insights are needed because the electricity system is moving away from centralised to decentralised nature. In Germany, Ireland and recently in South Africa, PV systems are taken up by customers. This causes big changes in the electricity system and may disrupt existing business models within distribution systems and municipalities. Changing the business model also means that the process of generation determination will be affected and must adapt to these changes. In order to understand these changes, both top-down and bottom-up modelling must be explored as a variants of modelling methodologies. These modelling approaches must take into consideration, the integrated planning approaches done at business or company level and be interfaced with national modelling so that there is a deeper understanding of the impacts that the bottom-up uptake of PV or wind can have on generation planning at national or state levels.

At end use level, distributors add the transmission and distribution costs and package all this in a tariff for their customers. The customers pays for the cost of the service provided for by the entire electricity chain. In the new changing transition, it means that tariffs will end up changing because as customers increase their installations of their decentralised systems, the cost of electricity will keep changing and at the end of the day will affect how generation is planned. Given the importance of demand response in future generation plans, coupled with reducing demand due to self-consumption from customers, it is of paramount importance to include price feedback into load forecasting. As prices of electricity change, the demand from customers will change and current forecasts do not cater for such changes.

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