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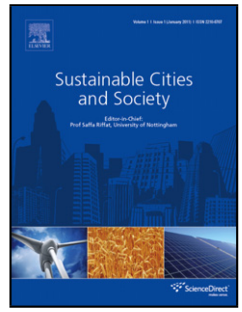

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Smart Grid Scenarios and their Impact on Strategic Plan – A Case Study of Omani Power Sector

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Highlights

- Different smart grid scenarios are developed
- Scenario costs and avoided cost benefit of smart grid is estimated
- Savings include avoided generation, T&D capacity and emissions
- Study concludes that benefit-cost ratio of DSM and minimum smart is above 1.0

Abstract

Electrical energy consumption if reduced during peak hours can result in the deferment of generation, transmission and distribution capacity addition. The postponement of capacity addition, or “avoided cost” is of promising value to electric utilities who can redirect financial resources for other purposes due to these offset costs. The reduction in energy consumption is achievable through smart grid implementation. Therefore, the utilities need to investigate whether upgrading their grid system to make it smarter is

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economically justifiable or not. Electricity companies have used the smart grid maturity model to assess their rating/ranking in different domains. The paper provides a framework for establishing future strategies and work plans as they pertain to smart grid implementations. The objective of this paper is to evaluate the demand-side management (DSM), energy efficiency measures and distributed generation benefits of smart grid in Oman. The developed scenarios include grid enhancement, customer contribution to the grid and both of these options simultaneously. The scenarios are analyzed for peak reduction and their benefits are calculated in terms of avoided cost of generation, transmission, distribution, and environmental costs.

Index Terms—Smart grid; renewable energy sources; energy planning; demand-side management; distributed power generation.

1. Introduction

In contrast to the conventional grid, the distribution system in a smart grid facilitates a two-way power flow between customers and electric utilities. The electricity customers can generate electricity using renewable energy systems at their premises and have the option to export energy to the grid at times that they select. In this way, customers become both producers and sellers, otherwise known as "prosumers", of electricity. Meters become smart with the capability of measuring electric energy in both directions and by utilizing the two-way communication system between customers and power utilities. Storage devices play an important role in levelling the load to store the excess of energy produced and release to the network when needed. As a whole, then, the system becomes more efficient and reliable and provides a better configuration to absorb high penetration of renewable energy sources compared with the conventional grids [1]. A smart power grid is equipped with the capability to control appliances at consumers' homes to save energy, reduce cost and increase reliability and transparency. A smart grid includes an intelligent monitoring system that keeps track of all electricity flowing in the system and thus has the capability of optimizing the network losses and self-healing in case of network problems [2]. Within recent years, there has been a significant and growing interest in smart grids, as well as a plethora of research conducted on their use, capabilities and benefits. [3]. A comprehensive review of socio-economic acceptability for smart grid development with about 175 references is provided in [4].

The modernization of the power system plays a vital role in improving the efficiency of the national power system network. In fact, the development of smart grids is likely to offer many tools and avenues towards improving demand-side management (DSM) and demand response (DR). For this reason, the governments, national electric utilities, and other stakeholders are encouraged to devise initiatives to improve DSM through potential conservation and load management programs and to integrate renewable energy sources. The following are some of the DSM benefits of smart grid technology that can be achieved on a national level [2] [5]:

- Real-time load monitoring helps forecast demand and thus reduce peak demand directly by allowing certain loads to be turned off or shifted to underutilized times;
- Increase in energy efficiency by incorporating smart devices;
- Support higher energy sales by motivating customers through pricing at the time of low demand and thus resulting in higher load factor for the same capacity;
- Reduction in peak energy losses;
- Makes distributed generation more practical through demand response, which can absorb large fluctuations in generator output;
- Plug in hybrid electric vehicle as a storage device;

- Optimize renewable energy resources;
- Better management of demand and supply results in reduction of overall reserve margin and spinning reserve requirement;
- Delay capital investment in generation, transmission and distribution equipment by optimizing existing assets and reducing peak demands.

The following is a brief review of some of the articles mentioned that deal with benefits of energy storage, demand response (DR) or demand-side management (DSM), and the environment in smart grid setting. In [6] the author has discussed The European Strategic Energy Technology Plan, (SET-Plan) about the European smart city vision and the role of zero energy buildings. According to this plan, renewable energy, energy storage, smart grids and plug-in vehicles are presented as the four pillars of energy systems of the post carbon society. In reference [7] the authors applied a two round policy Delphi process with a range of sectoral experts who discussed important drivers, barriers, benefits, risks and expected functions of smarter grids, to inform the development of smarter grids in the UK. The analysis of these expert views indicates broad consensus of the necessity for smarter grids, particularly for economic and environmental reasons. The benefits of an electrical energy storage system in a future smart grid are evaluated in [8]. The authors of the study have developed a simulation software that evaluates the benefits brought by operating an energy storage system (ESS) in response to multiple events on multiple networks. The simulations conducted have shown that operating an ESS embedded in the distribution network has a positive impact on the duties of voltage control and power flow management. The authors discussed wider implications of the results of their study of the role of ESS systems in future Smart Grids. In reference [9] the authors have analyzed the storages policy strategies to simultaneously satisfy heat and electricity demand through the efficient use of distributed generation units under demand response mechanisms. The study finds that the storage units reduce energy costs by 7-10% in electricity and 3% in gas charges. A survey of DR potentials and benefits in smart grids is presented in [10]. In reference [11] a review of DR in smart electricity grids equipped with renewable energy sources is presented. Moreover, a complete benefit and cost assessment of DR is added in the paper. A fast power demand response (DR) strategy involving both active and passive cold storages is presented in [12]. The paper presents the life-cycle cost-benefit analysis of active cold storages for building demand management for smart grid applications. In reference [13] an analysis on the low-carbon benefits of smart grid of China is presented. In [14] a DSM strategy based on load shifting technique for demand side management of future smart grids with a large number of devices of several types is presented. A heuristic-based Evolutionary Algorithm was developed for minimizing cost using a day-ahead load shifting technique. Simulations were carried out on a smart grid containing a variety of loads in three service areas. The simulation results showed that the proposed DSM strategy achieves substantial savings, while reducing the peak load demand of the smart grid. Evaluation of smart grids' impact on avoided cost of generation, transmission and distribution systems from load management viewpoint is addressed in [2]. Photovoltaic generation and battery systems for smart houses, in terms of a long-term expansion planning problem, are addressed in [15].

The electricity transmission and power distribution companies of Oman have shown interest in smart grid and have used the smart grid maturity model to assess their rating in eight different domains [16]. The rating is done between levels 0-5; with 0 being an entry or default stage and 5 being a pioneering stage. Table 1 shows all the levels and their description. The eight domains include: i) Strategy, Management, and Regulatory (SMR); ii) Organization and Structure (OS); iii) Grid Operations (GO); iv) Work and Asset Management (WAM); v) Technology (TECH); vi) Customer (CUS); Value Chain Integration (VCI); and viii) Societal and Environmental (SE). Table 2 shows all the domains and their brief description. The model developed by Software Engineering Institute of Carnegie Mellon University provides a framework for understanding the current state of smart grid deployment and capability within an electric utility and provides a context for establishing future strategies and work plans as they pertain to smart grid implementations [17]. Apart from this smart grid maturity assessment the Sultanate of Oman intends to undertake an Automated Meter Reading (AMR) implementation, focused on certain groups of high value customers. The scope of the project will include all the five distribution companies in the Sultanate of Oman. The system that will be realized in the framework of the project will manage AMR for the High Value Customers (HVC) and the typical functionalities of a modern smart metering infrastructure. The total number of accounts included in the AMR project is estimated to reach approximately 12,000 meters (accounts) by the end of year 2017 [18].

To further strengthen the resolve towards smart grid implementation, The Research Council (TRC) of Oman supported a project granted to Sultan Qaboos University (SQU) entitled “Enterprises Transition to Smart Grid in Oman” [19]. The objective was to identify the key drivers for implementing an enterprise geographical information system based Smart Grid in Oman and finding the best technologies that should be encouraged and demonstrated. One of the tasks of the project was to perform an analysis of selected strategic plans and scenarios for the smart grid impact on the Main Interconnected System (MIS) of Oman. The objective of this paper is to report the developed scenarios that included grid enhancement, customer contribution to the grid and both of these options simultaneously as well as an estimation of their benefits. The scenarios are analyzed for peak reduction and their benefits are calculated in terms of avoided cost.

The paper is arranged in six sections. Following the introduction, the second section discusses the methodology of the study. Section 3 explains the generation expansion planning model, generation and load data. The fourth section reports the estimated cost of upgrading the MIS to make it smarter. The fifth section discusses the smart grid scenarios, assumptions and results and finally the last section concludes the paper.

2. METHODOLOGY

The estimation of long-term benefits of smart grid is done by conducting the following steps. Figure 1 shows in detail the flowchart of the first step of the methodology and Fig. 2 shows the flowchart of the overall methodology.

1. Find an "optimal" generation expansion plan of least-cost with the base load forecast of 21 years starting from 2015 until 2035. This plan gives the capacity additions, energy generation, the operating and capital costs and the reliability of the generation system for 21 years. This case is called the business-as-usual or base load (BL) case. The software used to find the optimal generation expansion plan is Wien Automatic System Planning Package (WASP) [20]. The environmental costs related to BL case are calculated subsequently, from energy generation information from different power plants each year. The process of finding the least-cost plan is explained in Fig. 1.
2. Modify the base peak load forecast for each scenario. The scenarios are discussed in section five.

3. Re-optimize the long-term generation expansion plans for the modified load forecasts of different scenarios using the same reliability criteria and candidate plants as considered in the BL case. The environmental costs related to each scenario case are calculated, from energy generation information from different power plants each year, of that particular scenario case.
4. Calculate the avoided cost of generation from the difference between the base case and other scenarios' cases.
5. Estimate the avoided transmission and distribution (T&D) capacity cost by assuming that the share of generation, and T&D assets are approximately equally distributed in the power system [2, 5]. The share of T&D infrastructure spending in US is also almost same of generation infrastructure cost [21].

3. Planning Model and Data

A. Expansion Planning Model

The WASP software, developed for International Atomic Energy Agency (IAEA), is used in finding the optimal expansion plan for the power generating system [20]. The software is freely available to the member countries of IAEA.

WASP has the ability to find the optimal generation plan over a period of thirty years, with constraints provided by the planner. The optimum is evaluated using dynamic programming in terms of minimum discounted total costs.

The cost function used by WASP is represented by the following expression [22]:

Minimize:

$$Y_j = \sum_{t=1}^{T} [\,\overline{CC_{j,t}} - \overline{SV_{j,t}} + \overline{FC_{j,t}} + \overline{OC_{j,t}} + \overline{UC_{j,t}}\,] \quad (1)$$

Where:

UC is the unserved energy cost

OC is the operation and maintenance (O&M) cost

FC is the fuel cost

SV is the salvage value of capital costs

CC is the capital investment costs

The bar over the symbols represent discounted values to a reference/base year at a given discount rate *i*.

Y_j is the objective function attached to the plan *j*; Y_j has to be minimized among all *j*.

t is the time in years (1, 2, ... , T),

T is the length of the study period (total number of years).

The following relationship must be satisfied:

$$[G_t] = [G_{t-1}] + [A_t] - [R_t] + [C_t] \quad (2)$$

where:

$[G_t]$ is a vector containing the number of all generating units which are in operation in year t for a given expansion plan

$[A_t]$ = vector of committed additions of units in year t,

$[R_t]$ = vector of committed retirements of units in year t,

$[C_t]$ = vector of candidate generating units added to the system in year t,

$[A_t]$ and $[R_t]$ are given data, and $[C_t]$ is the unknown variable to be determined; the latter is called the system configuration vector or, simply, the system configuration.

The following constraint should be met by every acceptable configuration:

$$(1 + a_t)D_t \geq P(G_t) \geq (1 + b_t)D_t \quad (3)$$

which simply states that the installed capacity $P(G_t)$ of the system of year t must lie between the given maximum and minimum reserve margins, a_t and b_t respectively, above the peak demand D_t, of the year.

The reliability of the system configuration is evaluated by WASP in terms of the Loss-of-Load Probability index (LOLP). This index is calculated in WASP for each period of the year and the average annual LOLP as the sum of the period LOLPs divided by the number of periods.

If $LOLP(G_t)$ is the annual LOLP then every acceptable configuration must satisfy the following constraints:

$$LOLP(G_t) \leq K_t \quad (4)$$

where K_t is the limiting value given as input data by the user.

B. Generation Data

The generation expansion planning is undertaken for MIS from 2015 to 2035. The MIS has several interconnected power stations operating on natural gas as fuel with a number of generating units of different sizes of gas turbines and combined cycle units. The power stations are interconnected through 132 kV and 220-kV transmission lines. The total capacity of these stations is about 7000 MW (year 2015). The committed and retiring unit data are also provided for the study. The committed units are those which are expected to be inducted in the system within the first few years of the study. The candidate units are used for expanding the system. The candidates are selected based on their economic and technical suitability for the system. Three types of candidate units, open-cycle gas turbine of 91-MW and two types of combined cycle GT of 435-MW and 745-MW are used. The complete list of data that include net generating capacity, minimum loading level, fixed O&M, variable O&M, forced outage rate, scheduled maintenance days, net heat rate at minimum load and average incremental heat rate for each units can be found in [23].

C. Load Data

WASP employs the load duration curve model for energy calculation. The annual chronological hourly load curve of year 2014 is used to make load duration curves (LDC) for winter and summer seasons. These LDCs are then normalized and held constant throughout the study period. The peak load for year 2015 is 5653 MW and for year 2035 (the end of study period) is 17,724 MW with an initial load growth of 9% and then gradually reducing to 4%. Oman Water and Power Procurement Company (OPWP) evaluates electricity demand at the system level, including transmission and distribution system losses with consumer-level loads. This equates with the output of power generation plants at the delivery point(s) to the power system, excluding the internal power consumption of auxiliary systems [24]. The reduction in load growth in later years is assumed due to expected decrease of future oil and gas production in Oman. The downward oil and gas production makes the Omani GDP growth rate smaller than the current level [25].

The discount rate used for the study is 10.0% and the cost of unserved energy as 3.2 $/kWh.

D. Externality Costs

Power generation plants have several environmental concerns and have many types of emissions but the most important and significant are CO_2, SO_2, NO_x and particulates. Table 3 shows emission factors in kilogram per MWh of energy produced from gas-fired units and combined-cycle power plants taken from [2]. Table 4 shows the externality costs of different pollutants used in the study [2].

The costs of emissions are calculated by the following two equations:

$$Emissions\ in\ kg = Discounted\ energy\ of\ study\ period\ (MWh) \times Emission\ factor\ \left(\frac{kg}{MWh}\right) \quad (5)$$

$$Externality\ cost\ (\$) = Emissions\ (kg) \times Externality\ cost\ \left(\frac{\$}{kg}\right) \quad (6)$$

4. Cost of Upgrading MIS

The Electric Power Research Institute (EPRI) estimated the total cost of implementing a fully functional USA grid in 20 years for about 129.97 million homes between $338 and $476 billion [26]. Since smart grid is still a concept under construction and there are other factors in play, placing a price tag on smart grid is extremely difficult in the case of Oman. It is possible that due to economies of scale, the cost of making the grid smarter per household in the USA would be less compared to Oman, however, the cost of labor is significantly cheaper in Oman. The total number of MIS registered electricity customer accounts in year 2015 were 874,524 in which residential customers accounted for 74.8% of all customer accounts [27]. Therefore, for 654,144 residential customers, the cost of upgrading the grid would be between 1.7 and 2.4 billion dollars.

5. SMART GRID SCENARIOS, ASSUMPTIONS AND RESULTS

In order to estimate some of the smart grid benefits, four smart grid scenarios are developed [23, 28], beside the base case, based on studies done earlier in Oman [25] and Kuwait [29]. These scenarios are called: 1) base case; 2) minimum smart; 3) recommended DSM; 4) distributed generation (PV) and 5) hybrid (PV&DSM). Figure 3 shows scenarios in term of smart grid maturity levels in different domains (refer to Tables 1 & 2). The considered scenarios are explained below [23, 28]:

A. Scenario 1: Base Case

This scenario assumes that the utilities do not consider any smart grid integration nor any DSM measures (0 level of Table 1). The base case optimization results in a total system expansion cost of 27.84 billion dollars with a total addition of 15,571 MW and an average loss-of-load probability (LOLP) of 0.1291% that corresponds to a loss of load expectation (LOLE) of slightly less than 0.5 day/year. The target LOLE is less than 1 day/year. Figure 4 shows the total capacity each year versus the peak load. It may be noted from the Figure that there is a significant addition of generation capacity in year 2019; this is because there is already committed capacity that will be inducted in 2019. Further, Fig. 4 also shows that the capacity then decreases in 2020, due to the many planned retirements in the system.

B. Scenario 2: Minimum Smart

This scenario is based on a study done by the Japan International Cooperation Agency (JICA) Study Team [25]. It introduces Energy Efficiency & Conservation (EE&C) measures to enhance the efficiency of the power sector in Oman. Based on the technology used in these measures, they can be accounted for by introducing a basic level of Smart Grid technologies. The minimum smart case of utilities starts with somewhere between level 1 and 2 of eight domains (Table 1 & 2) in initial years and by the end of study period, the utilities move between level 2 to 3 of different domains as shown in Fig. 3.

The followings are the EE&C Measures that are used in this scenario:

1. Energy Management System.
2. Minimum Energy Standards and Labeling System.
3. EE&C Building Regulation.
4. DSM Tariff System.
5. Smart Meter (Automatic Meter Reading and Monitoring System).

The details of these measures and necessary assumptions can be found in [25]. The cost disbursements of these measures for different years, as outlined in the JICA study, are shifted two years and inflated by 3% each year for two years. The cost disbursement starts from year 2015 and continues till 2035. The investment costs are then discounted back to the base year of 2015. The total discounted investment costs needed to implement these measures are $658.98 million. For the effect of EE&C Measures, the JICA team has made three cases regarding the implementation of these measures.

1. Case 0.8: EE&C measures are introduced and the impact meets 80 % of the expectations.
2. Case 1.0: EE&C measures are introduced and the impact is 100 % as expected.
3. Case 1.2: EE&C measures are introduced and the impact exceeds expectations (120 %).

Since a detailed report by JICA is available online, the assumptions for the above cases are not reported here. According to these three measures, the peak load forecast is revised and shown in Fig. 5 along with the base load forecast. As the investment in the smart grid will take place in phases, the peak loads changes can be noted from the graph in phases. Table 5 summarizes the capacity addition, average LOLPs, total generation expansion costs and environmental costs of the three cases.

C. Scenario 3: Recommended DSM

This scenario is based on some recommended practices for efficient energy utilization which residential customers can follow without needing much investment from customers or the utility. The scenario is based on assumptions taken from a study done in Kuwait [29]. Recommended DSM can be carried out without investing much in smart grid technologies. Therefore, just awareness of level 1 of smart grid maturity level in seven domains and enabling of customer participation of level 2 is assumed (Fig. 3).

The assumptions for this scenario, derived from [29] and extended in [23], are described below. There are two DSM measures assumed in the residential sector. DSM1 is considered in air conditioning and DSM2 in lighting.

DSM1 Measure: Normally in almost all houses, the thermostat setting is put in the range between 70°F (21.1°C) to 75°F (23.9°C). In this scenario, a simple DSM measure is applied by increasing the thermostat setting from 75°F (23.9°C) to 78°F (25.6°C). The following are its assumptions:

- Contribution of Residential Sector (CRS) to the system peak demand = 70%. In spite of the fact that there is no such data that can differentiate the contribution of each sector towards system peak demand, the data about annual energy consumption from each sector is available [27, 30]. The annual residential sector energy consumption contribution to the overall power sector energy consumption is 47%, whereas the government sector is 12% and the commercial sector is another 22%. The government sector working hours are up to 2:30 pm and the small commercial shops and convenience stores called *baqalas* are closed from 2:00 to 4:00 pm [31]. This means that at the time of system peak demand, that occurs between 2:00-4:00 pm in summer, when the temperature is soaring around 50°C (122°F) the majority of the population is in their homes, hence the peak load is largely contributed from the residential sector. Therefore, in this study it is assumed that CRS to the system peak is 70%.

- The appliance Energy Consumption Share (ECS) of air conditioning is 70% [29]. It could be even higher during summer peak time but 70% is assumed.
- By changing the settings of thermostats mentioned above the Reduction in Electricity Consumption (REC) of air conditioners decreases by 15% (Kuwaiti study [29]). Similar results are reported in a case study, done in Riyadh, Saudi Arabia, where the authors claim that a 10% reduction in yearly cooling transmission load can be achieved per 1°C increase in thermostat setting [32].
- Assuming a 70% Participation Factor (PF) for DSM1, which means 70% of the participants are willing to increase the thermostat settings between 75°F to 78 °F. Results from a pilot study conducted by the JICA team show a similar volunteer participation factor [25].
- Since the system peak load occurs between 2:00 – 4:00 pm during summer time when almost everybody is using air conditioning, a Peak Coincident Factor (PCF) of 100%, therefore, is assumed.

Based on the above assumptions the system peak can be reduced to about 5% as follows:

Total reduction in peak load = CRS×ECS×PF×PCF×REC = 5.1%

DMS2 Measure: Here, it is assumed that high efficiency lighting is used by replacing the existing incandescent lamps 40 W and 100 W to compact fluorescent lamps (CFL), of rated power 7 W and 25 W respectively. The following are its assumptions.

- CRS to the system peak demand = 70% as noted above.
- The appliance ECS of lighting load is 12% [29].
- By replacing the lamps, the REC of lighting load decreases by 15.65% (Kuwaiti study [29]). The Kuwaiti study made an elaborate effort to calculate lighting load in different types of houses such as villas, apartments, traditional houses etc. The study's results demonstrated that percentage-wise, the reduction was very similar, regardless of the type of houses and number of lamps needed.
- As the system peak load occurs during the daytime, a PCF of 10% for lighting is considered here.
- Assuming that the majority of the population has already switched to using CFL, only 40% PF for DSM2 is used after two years.
- Based on the above assumptions, the system peak can be reduced to about 0.05% as follows:

Total reduction in peak load = CRS×ECS×PF×PCF×REC = 0.05%

As noted above, DSM2 contribution in reducing the system peak with these assumptions is just 0.05%, which on a system peak of 10,000 MW will reduce only 5 MW. Therefore, even if DSM2 is neglected it will not have much effect on the results. Based on the above assumptions the peak load forecast is modified and shown in Fig. 6. To implement Recommended DSM scenario, it is assumed that only administrative costs and some promotional costs would be incurred. Furthermore, it is assumed that residential customers will switch to efficient lighting voluntarily and even if a small fraction participates to replace lamps, DSM2 has a negligible effect as pointed out earlier on reducing the system peak. Therefore, a cost of only ten million dollars is assumed for such a program. Scenario 3 optimization results in a total system expansion cost of 26.07 billion dollars with total addition of 14,792 MW and an average LOLP of 0.1473%.

D. Scenario 4: Distributed Generation (PV)

This scenario assumes that some 10% of the residential consumers will install PV panels on their houses which could reduce the peak demand of their houses by 100%. The scenario assumes that the demand will not be affected until after 5 years when the grid is ready to integrate distributed generation at consumer sites. Distributed generation case of utilities is somewhere between level 3 and 4 of smart grid maturity in eight domains (refer to Fig. 3, Tables 1 & 2). The cost of upgrading the grid to this level would require between $1.7-2.4 billion as mentioned earlier.

The standard PV system modules and the cost used in this scenario are assumed the same as Sultan Qaboos University's Eco House [33]. The two-storied house features a compact form with around 280 m^2 built up area and a total height of 8.6 m. The house was designed to fulfil the living pattern of the modern Omani family while respecting social norms. The following are its assumptions:

- 20 kW total PV-system peak capacity
- Total system cost = $52,000
- 100% peak reduction per customer as the house can supply its peak demand with 20-kW peak system [33].

- 10% participation factor (residential sector only). 10% of the residential customers install PV panels on their homes.
- Total peak reduction in residential sector= 10% × 100%= 10%.
- Residential customer peak demand occurs at the same time as the system peak (100% coincident factor)
- Residential sector share to the system peak demand = 70%
- Total peak reduction on overall power sector= 10% × 70%= 7%
- The impact happening after five years when the smart grid integration of distributed generation is realized.
- The total investment for 10% of 654,144 MIS residential customers is following:
- (Total number of residential customer × 0.1) × 52,000 = 654,144 × 0.1 × 52,000 = $3.402 billion
- Discount rate 10%. Discounted back to 5 years, the cost is $2.112 billion.
- 50% cost subsidy provided by the Government. The cost for the subsidy is $1.056 billion. This assumption is appropriate, as the Omani Government is already subsidizing the residential sector with hundreds of millions of Omani rials each year [27, 30]. For example, 2015 MIS subsidy was 344 million Omani rials which amounts to approximately $890 million US dollars [27].
- Beside the above subsidy, it is further assumed that the upgrading of grid would cost $2.0 billion. Therefore, the total expenditure assumed is $3.056 billion.

Based on the above assumptions the peak load forecast is modified as shown in Fig. 6. It is important to note that the modified forecast is changed from 2020 onwards. Scenario 4 optimization results in total system expansion cost of 26.34 billion dollars with total addition of 14,320 MW and an average LOLP of 0.1410%.

E. Scenario 5: Hybrid (PV & DSM)

In this scenario, the impact of two previously studied scenarios, i.e., Distributed Generation and the Recommended DSM scenarios are combined. The assumptions are the same as the ones mentioned before for both scenarios. The hybrid case of utilities is somewhere between level 3 and 4 of eight domains (refer to Fig. 3, Tables 1 & 2).The modified load forecast is shown in Fig. 6. Scenario 5 optimization results in a total system expansion cost of 24.60 billion dollars with total addition of 13,393 MW and an average LOLP of 0.1367%.

F. Summary and Discussion of Results

The summary of results are shown in Table 6. The first two columns of the table show the scenario cases and their capacity additions until the end of the study period. The next five columns of the table are related to generation plan cost, T&D cost, investment cost for upgrading grid, environmental cost related to generation plan and the sum of all the costs. All the costs shown are discounted back to the base year of 2015 at a 10% discount rate. T&D infrastructure cost is assumed to be the same as generation plan cost because of the similarity in worth of asset distribution in the power sector. The last two columns of the table show the net benefit of avoided cost and benefit-cost ratio. The net benefit of avoided cost is calculated from the cost difference between base load case and the scenario cases. The benefit-cost ratio is avoided cost divided by the investment cost in upgrading the grid. It can be seen from the table that the recommended DSM of scenario 3 has the highest benefit-cost ratio. This is because the recommended DSM results in significant reduction in load change, resulting in huge savings in terms of avoided cost while almost negligible cost is needed to upgrade the system. Therefore, it should be seriously promoted not only in the residential sector but in other sectors too. The minimum smart cases of scenario 2 also give a benefit-cost ratio greater than 1.0. The advantage of minimum smart case is that if pursued the grid will become smarter and it has several other benefits beside demand-side management. The benefit-cost ratio of distributed generation of scenario 4 is 0.38. This is because a heavy investment is needed in upgrading the grid to ensure it becomes smarter and is able to integrate distributed generation. Further, a huge subsidy is needed to motivate customers to install PV panels. On the other hand, as the grid becomes smart and reaches the level of scenario 4, the benefits of scenario 2 can also be reaped, besides the additional benefits of smart grid, which are not assessed here. Scenario 5, which is a combination of scenarios 3 and 4, has clearly shown that in addition to the huge investment of scenario 4, if the recommended DSM is employed in parallel, the overall impact of benefit-cost ratio is greater than 1.

6. CONCLUSIONS

The Public Authority for Electricity and Water (PAEW) of Oman has invested in consultant studies to investigate the demand-side management potential. However, there is a lack of gravitas where DSM implementation is concerned. For example, the study carried out by Japan International Cooperation Agency in 2013 is not the first study of its kind. JICA conducted a similar study in 1997 and at that time, the DSM measures were easier to implement because the electric utility was vertically integrated and Government owned.

Recently, Oman has also shown some seriousness in smart grid implementation by investing in smart grid maturity assessment exercises and has planned to implement AMR and the typical functionalities of a modern smart metering infrastructure for some high value customers by the end of 2017. This paper is a step in this direction has attempted to show some of the economic benefits of smart grid. It has provided a framework for establishing future strategies and work plans as they pertain to smart grid implementations in Oman. Several scenarios are developed that included grid enhancement, customer contribution to the grid and both of these options simultaneously as well as an estimation of their benefits. The results of this study have shown that the recommended DSM has a huge potential of energy and capacity savings and does not need much of investment in smart grid. The other cases of Minimum smart scenario have also provided promising results and the benefit-cost ratio of these cases are also greater than one. The result of scenario 5, which is a combination of scenarios 3 (recommended DSM) and 4 (Distributed Generation), has clearly shown that in addition to the huge investment of scenario 4, if the recommended DSM is employed in parallel, the overall impact of benefit-cost ratio is greater than 1. The scope of this study was limited and did not estimate the other benefits of smart grid such as reduction in losses, reduced meter reading cost, reduced electricity theft, reduced outages, reduced restoration cost, reduced wide scale blackout etc. The study also did not take into account the other socio-economic benefits. Therefore, the study recommends expanding its scope to include some of the above benefits mentioned to make a strong business case for smart grid implementation by electricity companies.

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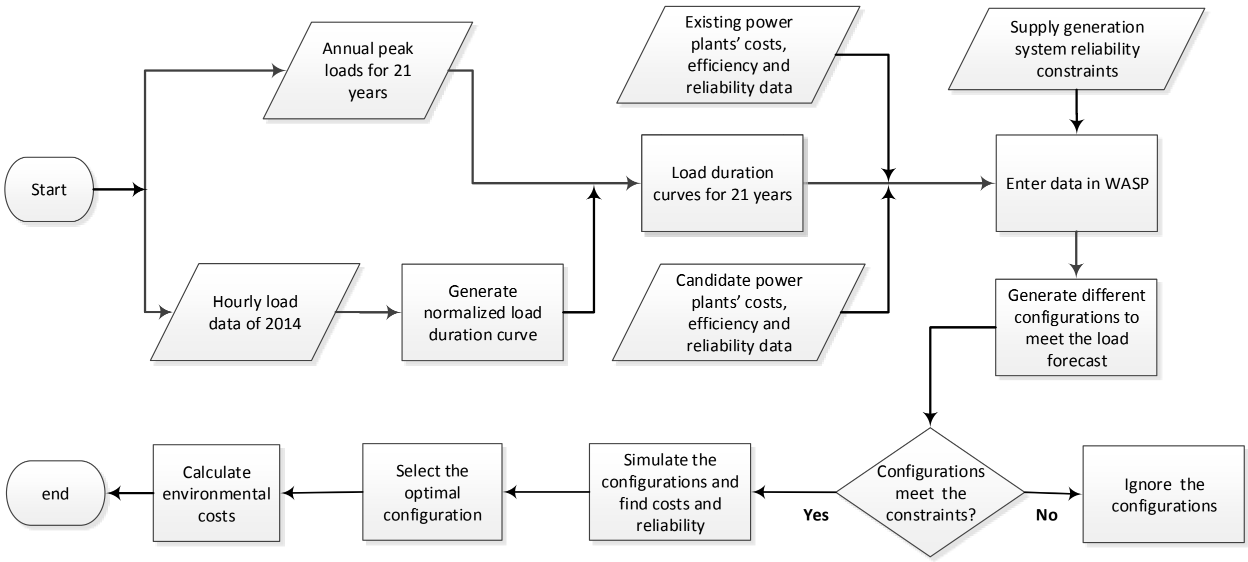

Fig. 1. Flowchart of the first step of the methodology.

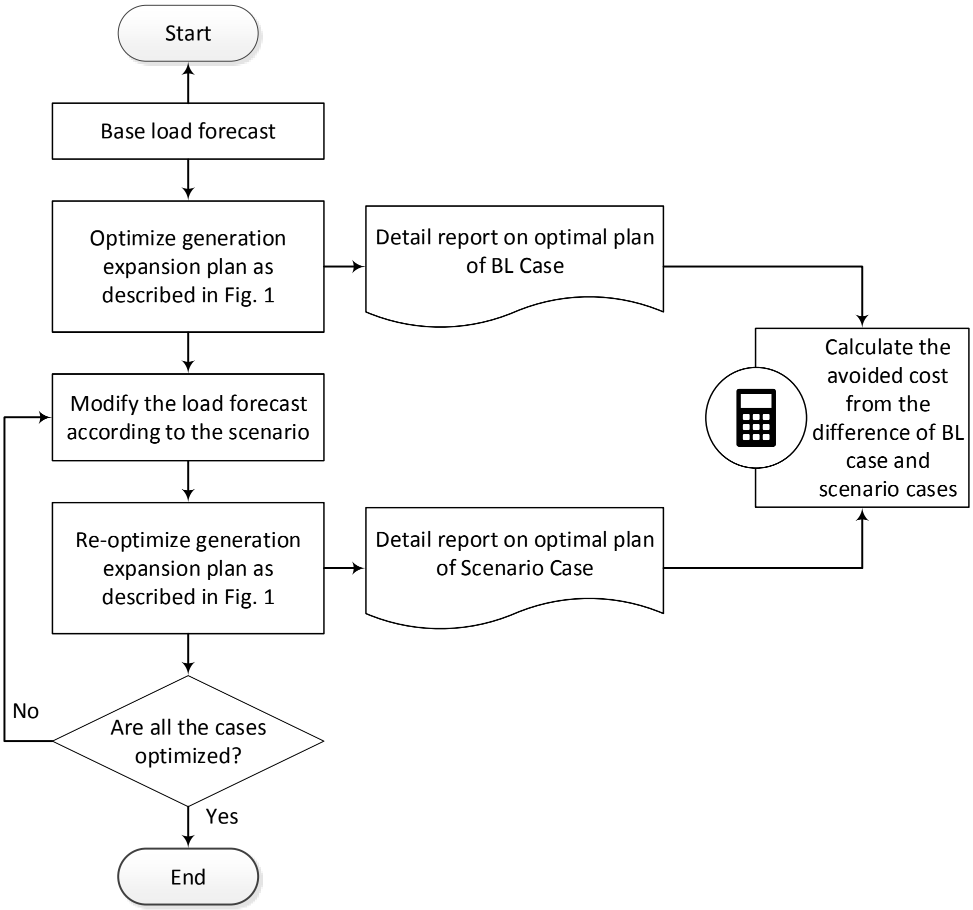

Fig. 2. Flowchart of the overall methodology.

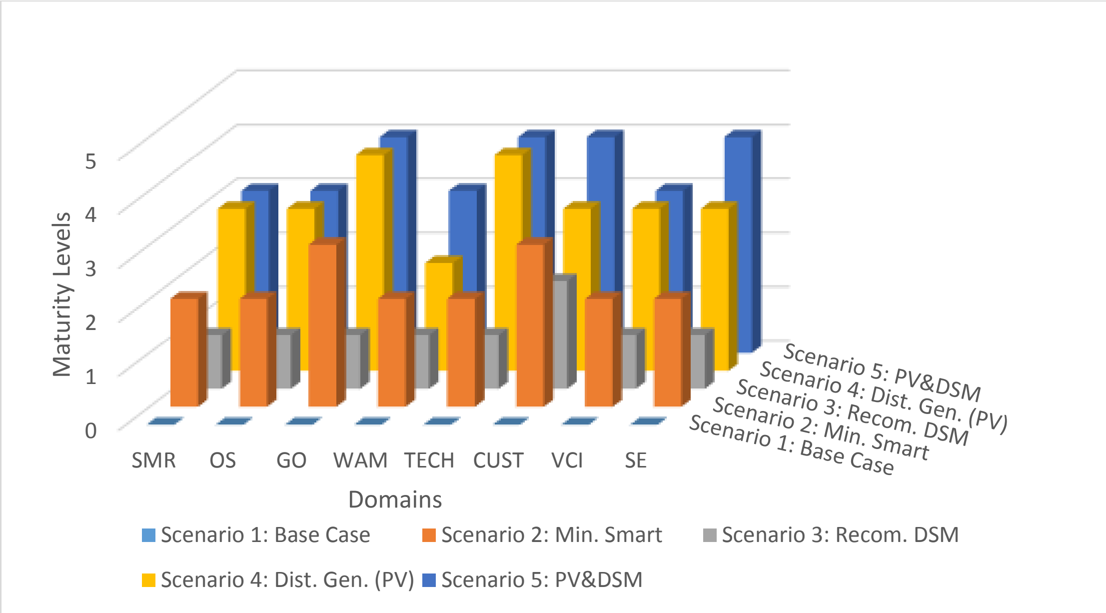

Fig. 3. Scenarios in term of smart grid maturity levels with respect to their domains (Tables 1 & 2).

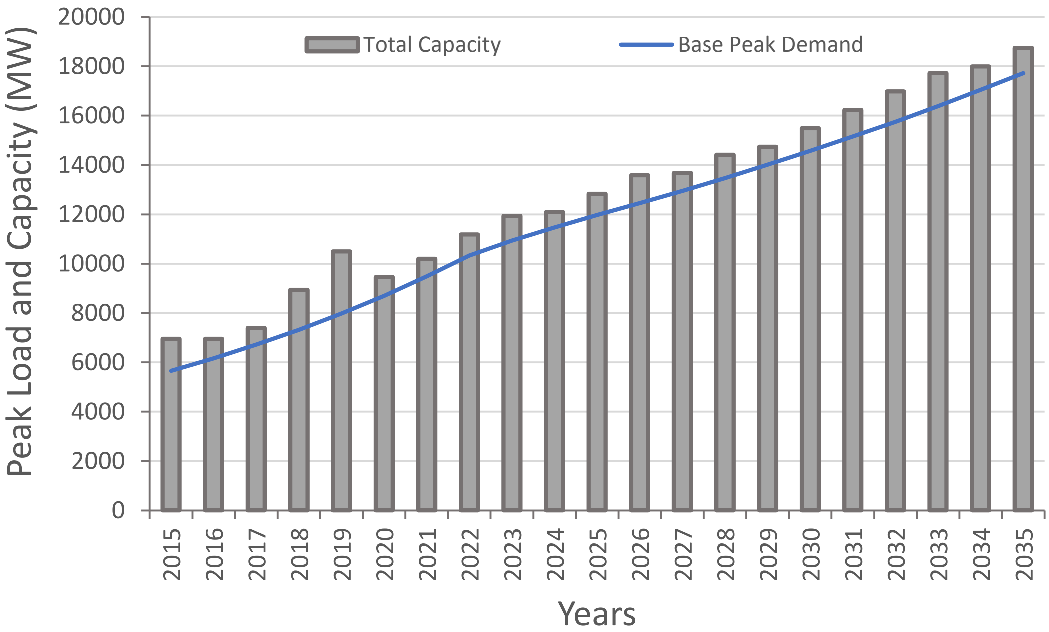

Fig. 4. Total annual capacity and peak load of scenario 1 (base case)

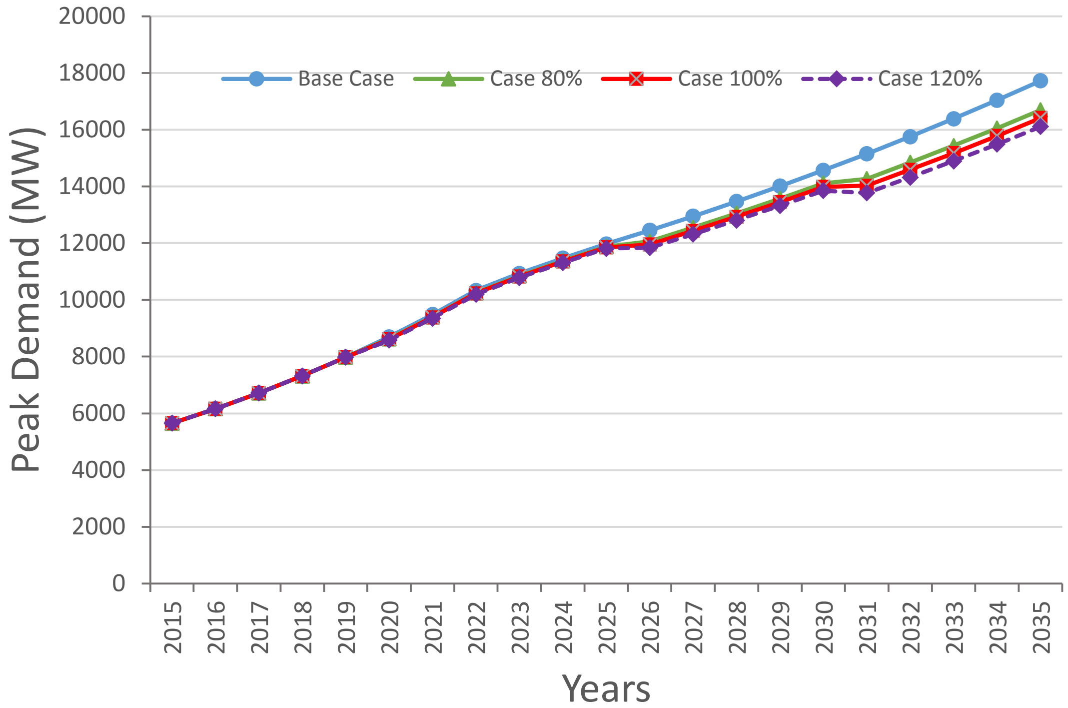

Fig. 5. Base Case load forecast and the modified load forecast of the three cases of scenario 2 (minimum smart)

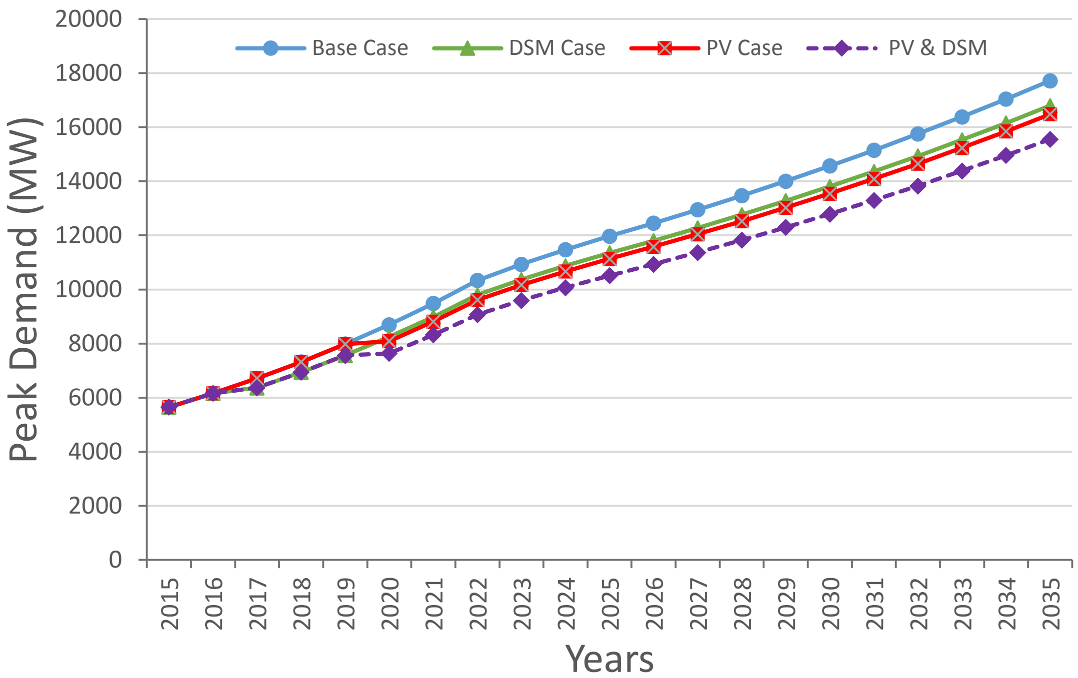

Fig. 6. Base Case load forecast and the modified load forecasts of scenarios 3 (DSM), 4 (PV) and 5 (PV+DSM)

Table 1. Smart grid maturity levels [17]

Levels	**Description**
5: Pioneering	Breaking new ground; industry-leading innovation
4: Optimizing	Optimizing smart grid to benefit entire organization; may reach beyond organization; increased automation
3: Integrating	Integrating smart grid deployments across the organization, realizing measurably improved performance
2: Enabling	Investing based on clear strategy, implementing first projects to enable smart grid (may be compartmentalized)
1: Initiating	Taking the first steps, exploring options, conducting experiments, developing smart grid vision
0: Default	Default level (status quo)

Table 2. Smart grind maturity models domains [17]

Domains	**Description**
Domain 1: Strategy, Management & Regulatory	Vision, planning, governance, stakeholder collaboration
Domain 2: Organization and Structure	Culture, structure, training, communications, knowledge management
Domain 3: Grid Operations	Reliability, efficiency, security, safety, observability, control
Domain 4: Work& Asset Management	Asset monitoring, tracking & maintenance, mobile workforce
Domain 5: Technology	IT architecture, standards, infrastructure, integration, tools
Domain 6: Customer	Pricing, customer participation & experience, advanced services
Domain 7: Value Chain Integration	Demand & supply management, leveraging market opportunities
Domain 8: Societal & Environmental	Responsibility, sustainability, critical infrastructure, efficiency

Table 3. Emission factors of gas-fired and combined-cycle plants [2]

Type	CO_2 (kg/MWh)	SO_2 (kg/MWh)	NO_x (kg/MWh)	Particulates (kg/MWh)
Gas-fired	550	0.0998	1.343	0.0635
Combined Cycle	367	0.0665	0.895	0.0423

Table 4. Externality costs of different pollutants [2]

Pollutants	Externality Costs in $/kg (Using lower Values)
CO_2	0.025
SO_2	7
NO_x	5.5
Particulates	33

Table 5. Summary of capacity additions, total generation expansion costs, average LOLPs and environmental costs of the three cases of Scenario 2.

Cases	**Capacity Addition (MW)**	**Generation Plan Cost (M$)**	**Average LOLPs**	**Environmental cost (M$)**
Case 0.8 (EE&C)	14,610	27,269	0.1432%	8,054
Case 1.0 (EE&C)	14,300	26,961	0.1439%	8,048
Case 1.2 (EE&C)	13,899	26,796	0.1394%	7,999

Table 6. Summary of Results

Scenario Cases	Capacity Addition (MW)	Generation Plan Cost (M$)	T&D Cost (M$)	Investment cost in Grid upgrade (M$)	Environmental cost (M$)	Total Costs (M$)	Net Benefit of avoided costs (M$)	Benefit-cost ratio
Scenario 1 Base Case	15,571	27,838	27,838	—	8,243	63,919	—	—
Scenario 2 Case 0.8 (EE&C)	14,610	27,269	27,269	659	8,054	63,251	668	1.01
Scenario 2 Case 1.0 (EE&C)	14,300	26,961	26,961	659	8,048	62,629	1,290	1.96
Scenario 2 Case 1.2 (EE&C)	13,899	26,796	26,796	659	7,999	62,250	1,669	2.53
Scenario 3 Recommended DSM	14,792	26,070	26,070	10	7,612	59,762	4,157	415.7
Scenario 4 Distributed Generation	14,320	26,395	26,395	3,056	7,843	62,744	1,175	0.38
Scenario 5 Hybrid (PV+DSM)	13,393	24,601	24,601	3,066	7,475	58,798	5,121	1.67