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Optimal Site Selection for Modular Nuclear Power Plants

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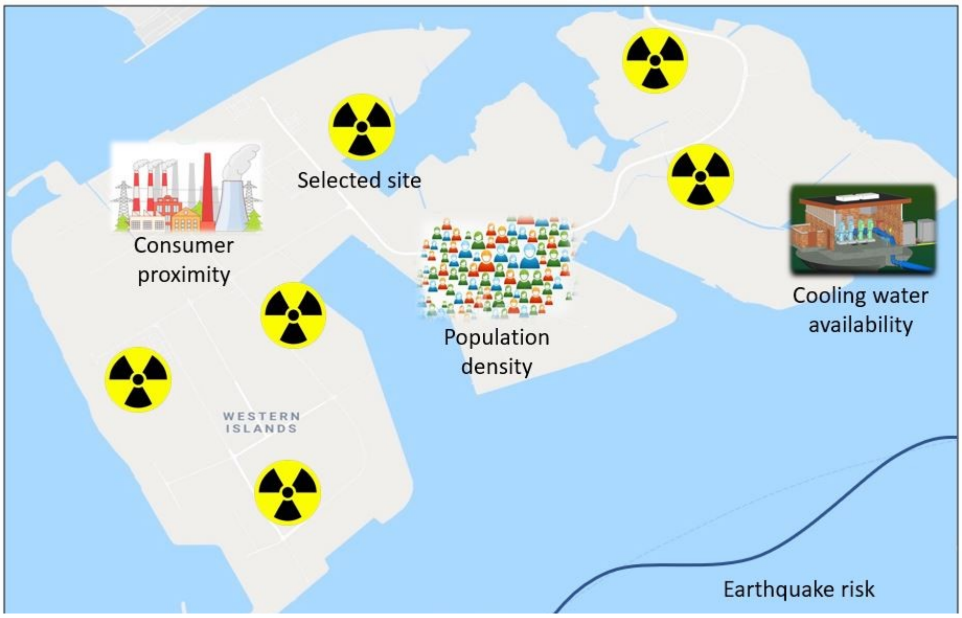
Abstract

Small Modular Reactor (SMR) is a small, compact version of a conventional Nuclear Power Plant (NPP) and holds much promise for the future. Installing SMRs in a region requires a series of carefully planned steps out of which site selection is a critical one. This paper proposes a novel mathematical model for evaluating potential land sites for their suitability of hosting a modular NPP. Most existing decision making tools for NPP site selection rely on qualitative information from the experts. These tools require significant resources and therefore can only be applied to a limited number of selected sites. The proposed model is a Mixed Integer Nonlinear Programming (MINLP) formulation which considers a variety of factors like cost, cooling water availability, earthquake risk, etc. to identify best locations for the SMRs in a distributed power system. A case study based on Singapore is taken to demonstrate the capabilities of the model by finding the optimal locations of modular NPPs in Singapore. The model offers a preliminary platform for carrying out further extensive studies.

Highlights

- Brief overview of SMRs and its feasibility for Singapore
- MINLP model for optimal site selection of SMRs
- A case study on JPark Simulator
- Model can serve as a preliminary feasibility analysis tool



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1 Introduction

The world energy sector is seeing a significant increase in demand during the last few decades and is projected to keep up the trend in the coming years. Almost 80% of this demand is still met by fossil fuels even with the recent developments in renewable energy technologies. The rising concerns about climate change and sustainability of fossil fuels are pressuring countries to shift their energy policies towards cleaner and sustainable energy sources. Many developed nations like USA, Germany, France etc. have pledged to decrease their GHG emissions significantly in the near future.

Conversion to renewable energy sources like wind, solar, hydroelectric, geothermal etc. is an excellent way to reduce carbon emissions. These energy sources provide energy with minimum environmental impact. Some countries like Iceland and Albania are already meeting their energy demand with 100% renewable energy and many others like Germany and Denmark are on their way. Although there has been significant progress in the renewable energy technology many researchers believe that a complete transformation to the renewables is impossible in the near future [12, 33]. The major challenge is their seasonal nature which creates a serious problem for the power grid stability. These renewable energy systems need to work in tandem [2] with other reliable energy sources for the smooth functioning of a power grid.

Nuclear energy is an option that can provide reliable base load power at reasonable prices and minimum carbon emissions as shown in Figure 1. While nuclear power looks good on paper, it comes with its own shackles. Its major setback is the lengthy plant construction periods of up to 15 years. This creates a huge array of problems like cost overruns, policy changes [32] and shift in regulatory requirements. The safety concerns and the public perception against nuclear power add to the problem. Last but not least, the prohibitive capital cost for a conventional NPP is a significant deterrent for many countries.

Much research exists on making nuclear power more affordable, safe and easier. This research focuses on making small, factory-built nuclear reactors that can be readily plugged into an existing power grid [35]. These works represent a paradigm shift in power generation from a large conventional reactor with a centralised power grid to one that of several modular reactors with a distributed generation framework [23]. The major advantages of a distributed framework will be its self-sufficiency and reliability. Most modular reactors can work for several years without refuelling [19], so they can be installed in remote regions or regions with no natural resources for energy production. Another advantage is that they occupy a smaller area compared to conventional NPPs and can be easily integrated into the existing power grids which makes them attractive for countries with land scarcity.

Selection and placement of NPPs at appropriate sites will be important in the development of a distributed framework. NPP should provide energy at the lowest cost and should minimise the risk to the surrounding area. There have been a few studies that analyse the feasibility of a potential site for a nuclear power plant [13, 21]. Most of these studies use multi-criteria decision methods like TOPSIS [8] and require extensive knowledge about the site before they can be implemented. These methods are computationally expensive and are conducted after a site is chosen as a potential candidate for a nuclear power

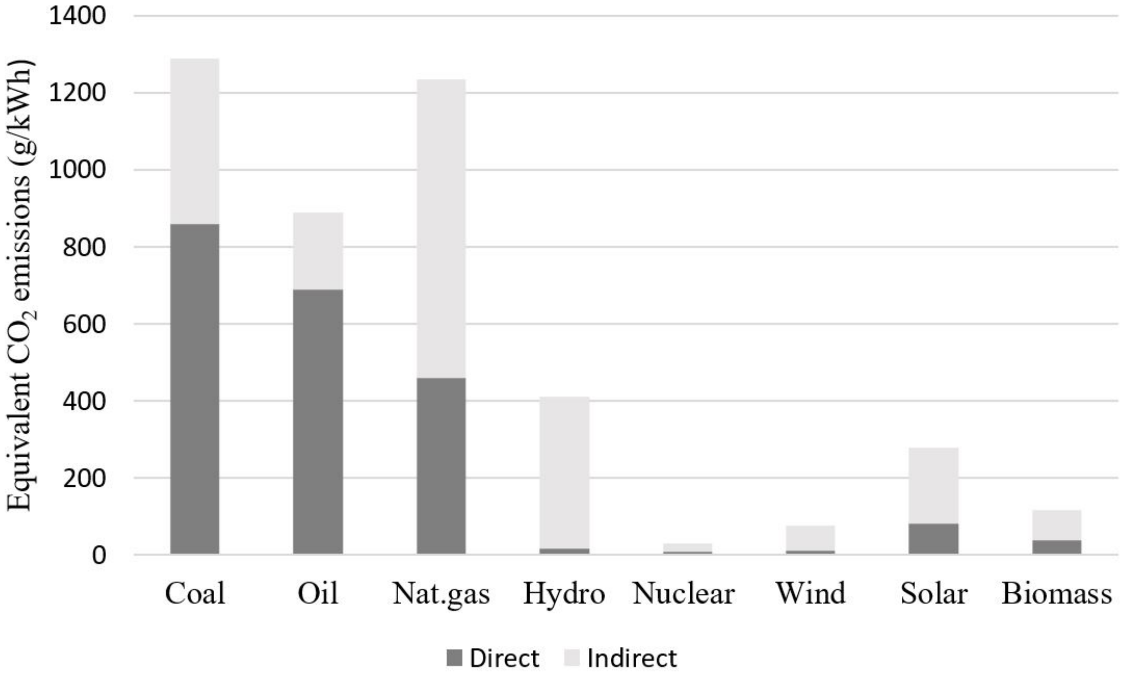

Figure 1: *Equivalent carbon dioxide emission factors for different power generation technologies.*

plant project. At present, there are no quantitative evaluation methods that can conduct a preliminary analysis of all the available sites in a large region and determine suitable locations for modular nuclear power plants.

This paper provides a brief overview of the recent developments in modular nuclear reactor technology and evaluates its potential for Singapore. It also proposes a model capable of determining the best suited locations for a modular nuclear power plant in a region based on the power demands. The model uses an ontology based knowledge base for accessing the financial and geographical information related to a particular site. The capabilities of the model is demonstrated by conducting a case study on the JPark Simulator(JPS).

2 Small Modular Reactor (SMR)

According to the International Atomic Energy Association (IAEA), a SMR is a nuclear reactor with a power output of less than 300MW. A typical SMR (see Figure 2) consists of two sections: a power module and a power generation assembly. The power module houses the reactor core with the fuel rod assembly where nuclear fission generates heat. This heat is transferred via an appropriate coolant to generate steam. The steam is then sent to the power generation assembly where it enters a Rankine cycle to generate power.

Most SMR designs have many enhanced safety features [6]. These include power modules engulfed in steel containment vessels placed underground in a pool of water. Some SMRs even have natural coolant circulation systems as shown in figure 2 wherein the coolant keeps circulating even when there is a power disruption [9]. The power modules from several SMR units manufactured by the same vendor and located at the same site can be horizontally integrated to feed a single power generation assembly that can be operated from a single control room.

Most SMR designs available today are generation IV reactors [5] that will be commercially deployed by 2030. Some major players in the energy market like Westinghouse, Babcock & Wilcox are in the process of perfecting their modular reactor designs, while facing tough competition from newcomers like Nuscale power [16]. Most favoured nuclear reactor technologies for the modular design are (1) Pressurised Water Reactor (PWR) [6, 36] and (2) Liquid Metal Cooled Reactor (LMCR) [1, 34]. PWR and LMCR technologies differ primarily in the reactor coolant. The SMR designs may also differ in their fuel capacities and refuelling periods [19]. Small reactors without on-site refuelling can operate for up to 30 years without any additional fuel requirement.

Besides a compact design and enhanced safety features, a major advantage of an SMR is its factory fabrication. This leads to faster installation periods and makes the integration of SMRs into an existing power grid much easier. An SMR with its low capacity might lead to a higher operational cost [24]. However, the designs of a large-scale NPP and modular NPPs are significantly different, and this may not necessarily hold true [22]. The factory fabrication of SMRs makes their transportation and assembly much easier. This combined with the ease of capacity additions and fewer operational components enhance the economic performance of an SMR significantly [7].

Based on the above discussion it can be inferred that the capital cost associated with an SMR unit depends primarily on the type of the reactor and its capacity. Another important feature that affect the capital cost is the horizontal integration of several units of SMRs having the same design and type. The improved resource sharing and efficiency of the resulting network can help save a significant percentage of the capital cost. Hence it is necessary to understand the properties of the various SMR designs for the successful execution of the model.

3 Site selection

It is desired to evaluate the option of having a network of SMRs providing power for a region. Its demand can be represented in terms of P load points $(p = 1, 2, ...P)$ with known discrete demands D_p, $(p = 1, 2, ...P)$. Preliminary studies have identified S potential sites $(s = 1, 2, ...S)$ in the region for locating the SMRs. Each site has a fixed area A_s $(s = 1, 2, ..S)$ to hold SMRs.

Several factors must be considered while locating SMRs at a given site:

Consumer proximity: Sites closer to the load points will reduce power transmission losses, hence are more attractive.

Capital cost: Sites with larger areas will offer the economies of scale, as multiple power modules of the same type can be integrated to reduce costs.

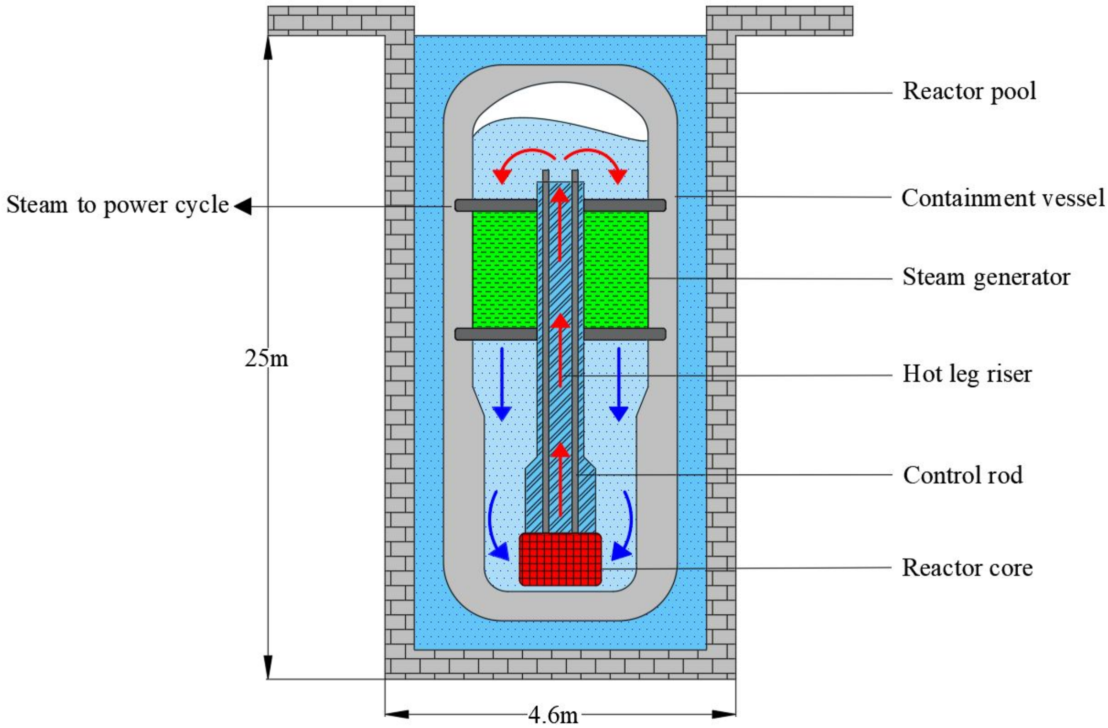

Figure 2: *Power module of a typical SMR with natural coolant circulation system.*

Population density: Sites with lower population densities are better from a safety perspective.

Cooling water availability: Every nuclear reactor requires a steady and reliable source of cooling water for emergencies. Sites closer to such supplies should be preferred.

Seismic risk: Sites near a seismic fault line should be avoided to minimise the risk of earthquakes and tsunamis.

After the sites are chosen, the following properties of the SMR modules for a particular site need to be determined:

Type: Based on the designs mentioned in the literature several types of SMRs are available. Deploying several units of a particular type to a site leads to horizontal integration that can cut down on the capital cost. Hence only one type of SMR is considered for a particular site in this model.

Capacity: Once the type of SMR is fixed, the output power capacity needs to be determined. SMR designs from most manufacturers have power modules with a rated power capacity and hence each type of SMR is assumed to have one fixed capacity.

Number of units: Finally the number of SMR units that need be placed at a particular site has to be obtained. Larger number of units at a site can reduce the capital cost significantly but will cause an increase in the risk associated with the immediate neighbourhood.

Given these site selection priorities, we can state the site selection problem as follows.

3.1 Problem Statement

Given:

- P load points ($p = 1, 2, ..., P$), their geographical coordinates, power demands D_p.
- S potential sites ($s = 1, 2, ..., S$), their geographical locations, available areas A_s and distances d_{cs} to the nearest cooling water sources.
- T SMR designs ($t = 1, 2, ..., T$) which can have i ($i = 1, 2, 3, ...I_t$) units, power generation rates F_t of a single unit, area UA_t required for a single unit and capital cost C_{it} for i units of type t.
- The project has a life span of L years.
- Capital cost correlations for integrating multiple identical power modules available from SMR vendors.
- The probabilities Pf and Pe_s of reactor failure and occurrence of an earthquake at a particular site.
- The cost per unit length μ_s of the cooling water pipeline.

Obtain:

- The sites to host SMRs.
- SMR types for each selected site.
- Number and capacities of SMRs at each site.
- The amount of power delivered by SMR network to the respective load points.
- The capital cost associated with setting up the SMR network.

Aiming to:

- Minimise the risk to the entire population living in proximity to the SMR network.
- Minimise the cooling water pipeline costs.
- Minimise the seismic risk associated with the network.
- Minimise the total capital cost of the network.
- Minimise power transmission losses in the entire network.

Assuming:

1. The power is delivered directly from the source to the load point. There are no substations involved since the system is distributed.

2. Transmission loss is considered as a linear function of the distance and power delivered.
3. The system is to be designed for the peak demand which accounts for power losses and includes a design factor for dealing with unexpected scenarios.
4. Each site will have only one cooling water pipeline and its diameter will depend on the number of units placed at the site.
5. Every chosen site will have one steam generation assembly whose area is a fixed known constant.
6. The effect of weather conditions on radiation leak in the event of a reactor meltdown is not considered.

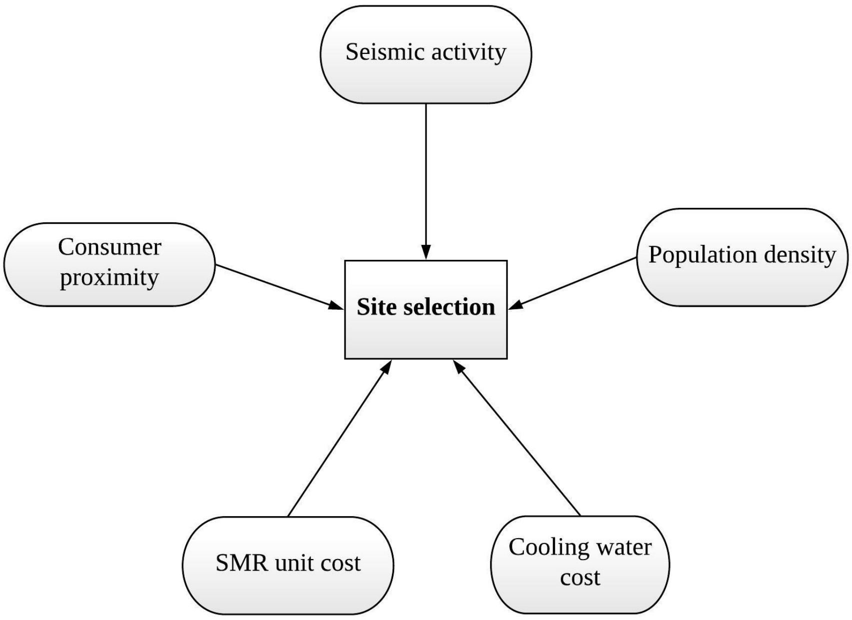

Figure 3: *Factors affecting the site selection.*

3.2 Optimisation problem formulation

Let y_{its} be a binary variable which is defined as:

$$y_{its} = \begin{cases} 1 & \text{if site } s \text{ have } i \text{ units of type } t \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

subject to:

$$\sum_{i=1}^{I_t} y_{its} \leq 1, \tag{2}$$

where I_t represents the maximum number of units of type t that can be integrated. The maximum number of units that can be integrated in a site is limited [15] to ensure the safety and design parameters of the units are not violated.

Define f_{sp} as the power supplied by site s to load point p. The total power supplied to a load point must equal its demand. Hence,

$$\sum_{s=1}^{S} f_{sp} \geq D_p. \tag{3}$$

Each site s must have the capacity to supply the requested powers to various load points. In other words,

$$\sum_{t=1}^{T}\sum_{i=1}^{I_t} iF_t y_{its} \geq \sum_{p+1}^{P} f_{sp}. \tag{4}$$

From eq. 1 and 2, we can derive the following surrogate constraint, which although redundant in the continuous sense tightens the MINLP formulation:

$$\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{i=1}^{I_t} iF_t y_{its} \geq \sum_{p+1}^{P} D_p \tag{5}$$

The process of site selection for a modular NPP requires careful consideration of multiple factors. Figure 4 gives a brief overview of the factors considered in this model. The capital cost associated with the SMR network is one such factor. If C_s represents the total annualised capital cost of all the units at site s and C_{it} represents the capital cost of i units of type t then:

$$C_s = \sum_{t=1}^{T}\sum_{i=1}^{I_t} \frac{C_{it} y_{its} D}{(1-(1+D)^{-L})}, \tag{6}$$

where D represents the discount rate and L the project life span. The capital cost function C_{it} of an SMR can be reduced significantly through SMR integration. It is a function of the type of SMR and should be provided by the SMR manufacturing company.

The maximum number of units that can be placed in a potential site is limited by the available area at site A_s and the area UA_t required for a single power module of an SMR of type t. i.e.,

$$\sum_{t=1}^{T}\sum_{i=1}^{I_t} y_{its} iUA_t \leq A_s. \tag{7}$$

The available site area A_s is obtained by subtracting the area required for steam generation assembly from the total area of the site.

Let z_s be another binary variable which is defined as:

$$z_s = \begin{cases} 1 & \text{if site } s \text{ is chosen for hosting SMRs} \\ 0 & \text{otherwise} \end{cases}, \tag{8}$$

subject to:

$$z_s \leq \sum_{t=1}^{T}\sum_{i=1}^{I_t} y_{its}, \tag{9}$$

and for any reactor of type t,

$$z_s \geq \sum_{i=1}^{I_t} y_{its}. \tag{10}$$

The annual transmission losses t_{sp} involved in distributing the power from the potential site to load point increases as the distance d_{sp} and the power transmitted from the s^{th} potential site to the p^{th} load point increases as shown in the equation:

$$t_{sp} = \alpha \sum_{t=1}^{T} \sum_{i=1}^{I_t} d_{sp} f_{sp} z_s, \tag{11}$$

where α represents the monetary loss in transmitting a single unit of power over a unit distance over a period of 1 year.

Similarly, the cost of providing cooling water to a potential site location needs to be considered. The distance to the nearest cooling water source d_{cs} can be considered as the measure of cooling water availability in a potential site. The annualised cost PC_s required for setting up a pipeline to draw this water from the source at the required volumetric flow rates can be written as:

$$PC_s = \sum_{i=1}^{I_t} \frac{\mu_s d_{cs} y_{its} D}{(1-(1+D)^{-L})}, \tag{12}$$

where μ_s represent the cost per unit length of the pipeline. It depends on the cooling water flow rate required which in turn is a function of the cooling water requirement for each type of reactor and the number of reactor units at a particular site. μ_s can be expressed as:

$$\mu_s = 96 \sum_{t=1}^{T} \sum_{i=1}^{I_t} \sqrt{iQ_t} y_{its}, \tag{13}$$

where Q_t represents the volumetric flow rate required for a single SMR unit of type t. The detailed calculations for the piping cost estimation is provided in Appendix A.

The placement of a modular NPP at a potential site poses some safety and security concerns to the neighbourhood areas. In this context, the neighbourhood of a particular potential site can be considered as the region around the reactor that will incur significant damage in the event of a radiation leak. The radius of this region depends on a variety of factors including weather conditions, reactor power output etc [10]. The radius r_s of the neighbourhood can be written as a function of reactor capacity as shown in the equation:

$$r_s = r_o \sum_{t=1}^{T} \sum_{i=1}^{I_t} \sqrt{iF_t} y_{its}, \tag{14}$$

where r_o represent the neighbourhood radius for a SMR unit of capacity $1MW$. The site selection model should tries to choose sites such that the risk to neighbourhood population remains minimum. The annualised risk function to the associated neighbourhood RN_s can be calculated as follows:

$$RN_s = \frac{P_f H \sigma_s D}{(1-(1+D)^{-L})}, \tag{15}$$

where H represent the average monetary value of a human life, σ_s is the population within the radius r_s from the site. P_f represents the probability of having a reactor failure. There have been several approaches to quantify this probability [31]. Most of the earlier studies have used a Probabilistic Risk Assessment (PRA) [26] approach wherein they identified different pathways that could lead into failure of a particular reactor. But after the Chernobyl disaster of 1986 there were significant debates in the scientific community to replace PRA with risk assessment based on observed data [18]. Most of the recent studies utilise the latter approach for the probability calculations and we have used this in the model. So, the probability of failure is considered to be independent of the type and capacity of the reactor.

The earthquake risk associated with a region also requires consideration. The probability Pe_s of having an earthquake at a potential site s during the duration of the project depends on a variety of factors like distance to the nearest fault line, soil composition etc. The risk function associated with earthquakes for the SMR can be written as:

$$RE_s = P_u D \frac{\sum_{t=1}^{T} \sum_{i=1}^{I_t} Pe_s \theta_{it} C_{it} y_{its}}{(1-(1+D)^{-L})}, \tag{16}$$

where P_u is the median probability of unacceptable performance [37] of secondary equipment in a SMR. It represents the percentage of damage an earthquake can create for the secondary equipments in a nuclear reactor. The primary equipments which include the reactor and containment vessel are not considered for this study as they are designed to withstand these phenomena. The cost of secondary equipments can be considered as a fraction θ_{it} of the total capital cost of the plant.

The Total Annualised Cost (TAC) function that considers all these factors can be written as:

$$z = \min_{d_{sp}, C_s, \rho_s, P_{es}, dc_s} \sum_{s=1}^{S} \left[C_s + \sum_{p=1}^{P} t_{sp} + RN_s + RE_s + PC_s \right] \tag{17}$$

The objective function is expressed in this manner for analysing the effect of different factors on the results easier.

4 Case study: JPark Simulator (JPS)

JPS is a smart system that provides an imaginary virtual representation of the EIP in Jurong island, Singapore [39]. Singapore is a small island of 700 km^2 area which consumes about 45 TWh of energy per year and almost 95% of this power is generated from natural gas [11]. Singapore does not have any indigenous natural gas deposits so, it depends heavily on natural gas imports from its neighbours Malaysia and Indonesia. Natural gas is delivered to Singapore mostly through pipelines [4] and shipping carriers. This leaves Singapore vulnerable to potential supply interruptions and price hikes.

Natural gas is a greener source of energy in comparison with its alternatives coal and diesel. Many researchers even consider it as the transition fuel towards a carbon free energy economy [38]. But there are rising concerns that the life cycle carbon emissions from natural gas which takes into account the methane leakage during the process could offset the benefits of burning natural gas over other fossil fuels [14]. These concerns along with the potential vulnerabilities in the supply chain have made Singapore look for alternate options.

There have been several studies looking into potential alternative energy sources [20] for Singapore like solar, wind, tidal, biomass etc. But most of these sources with the exception of solar and geothermal were found infeasible for Singapore. The lack of clear skies and the issue of energy storage systems will limit the extent of solar power penetration. The potential of geothermal power is also limited as it cannot be deployed in a large scale due to the current technological limitations.

Nuclear power is another alternative for Singapore [27] that should be considered further. Nuclear reactors can provide reliable energy for a long period of time without frequent refuelling. In 2010 Singapore government conducted a pre-feasibility study [25] to analyse the various technologies available for a nuclear reactor and its suitability for Singapore. The study took about two years to complete and it concluded that most of the conventional nuclear technologies are infeasible for Singapore. The study also proposed that Singapore should closely monitor the advances in the field and not completely rule out the possibility of a nuclear power plant.

Singapore being a small, densely populated island, cannot withstand the after effects of a nuclear fallout [28]. This combined with the strong public perception against conventional nuclear technologies [13] makes setting up of a nuclear power plant a political and safety nightmare. However, the SMR designs, mentioned in the paper tries to address these concerns and provides hope for a nuclear powered Singapore [17].

4.1 Feasibility for Singapore

The enhanced safety features along with the compactness of design make SMR a viable option for Singapore. A recent study that analyses the suitability of SMRs for different countries ranked Singapore as the best suited nation for implementing this technology [3]. There are several factors that have to be analysed for determining the feasibility of SMRs for a country. First and foremost the country should be financially stable to afford the initial investment involved in the deployment of SMRs. A lot of statistical indices like per capita GDP, the rate of GDP growth and energy consumption rate can be used to quantify this. Singapore being a developed nation performs well on these parameters [30]. Another factor is the size and technological sophistication of its power grid. Singapore has a power grid with a capacity of around 13 TW and has one of the most stable power grids in the world with average interruption of less than one minute per customer per year. The government policies regarding carbon emission reduction and the ease of starting a new business also play a major role. Singapore was ranked as the number one country in terms of the ease of starting a new business and its government is committed to a carbon free future. So, it can be concluded that Singapore is an excellent location for deploying the SMR technology.

In this paper, we have used the proposed model to find the best suited locations for modular nuclear power plants in the JPS which is an approximate virtual representation of the EIP in Jurong island. JPS has an existing power grid capable of providing power to its occupants. The SMRs are supposed to replace these power generation facilities and provide carbon free power to the EIP. The modularity integrated into the design of an SMR enables them to be easily transported to the required region and be plugged into an existing power grid.

4.2 SMR properties

The PWR designs of two companies are considered for the case study. Most of the data pertaining to nuclear reactor design is kept confidential because of its sensitivity and the designs are patent protected. Because of these reason the names of the companies are not revealed and they will be referred to as Company 1 and Company 2. Table 1 shows the reactor data available in the public domain for these two type of reactors. The cooling water requirement for Company 1 was not available in the public domain, so an Aspen Plus model of the power plant system was created to calculate it. The current facilities in Aspen are insufficient to successfully model a nuclear reactor, but the power cycle used in a nuclear power plant is similar to the ones used in other power plants and can be modelled in Aspen. In the model, the output from the reactor (primary water stream) is considered as an energy stream that can heat up water (secondary water stream). The properties of this stream depend on the capacity and type of the reactor used. The properties listed in Table 2 were used to execute the Aspen model.

Based on the obtained values for the cooling water flow rate, the cooling water pipeline dimensions and its cost could be determined. The pipeline was assumed to be made of stainless steel with a 1 inch thickness pipe. When more SMR units are placed in a site the cooling water requirement and the pipeline diameter increases proportionately.

The model requires the correlation for how the capital cost varies with number of units of the reactor. The capital cost of a single unit for both the designs were taken from their websites. Company 1 has mentioned that they can achieve a 20% reduction in capital cost by integrating 12 of their modules together. Hence it was assumed that the capital cost per unit decreases linearly as the number of units increases from 1 to 12. Since no such data was available for the Company 2 design it was assumed that there was no integration and hence no reduction in capital cost. The maximum number of units allowable at a site was restricted to 12 for Company 1 SMRs and 6 for Company 2 SMRS.

Based on the obtained values for the cooling water flow rate the cooling water pipeline dimensions and its cost could be determined. As the power delivered by a site increases the diameter of the cooling water pipeline increases proportionately. The probability of having a reactor failure based on literature can be approximated to once in 3750 years [31]. Also, the neighbourhood radius around the reactor increases proportionately with the power output of the site . A radius of $100m$ is considered for a SMR of $1MW$ capacity. Equation (12) was then utilised to calculate the resulting neighbourhood radius for a potential site.

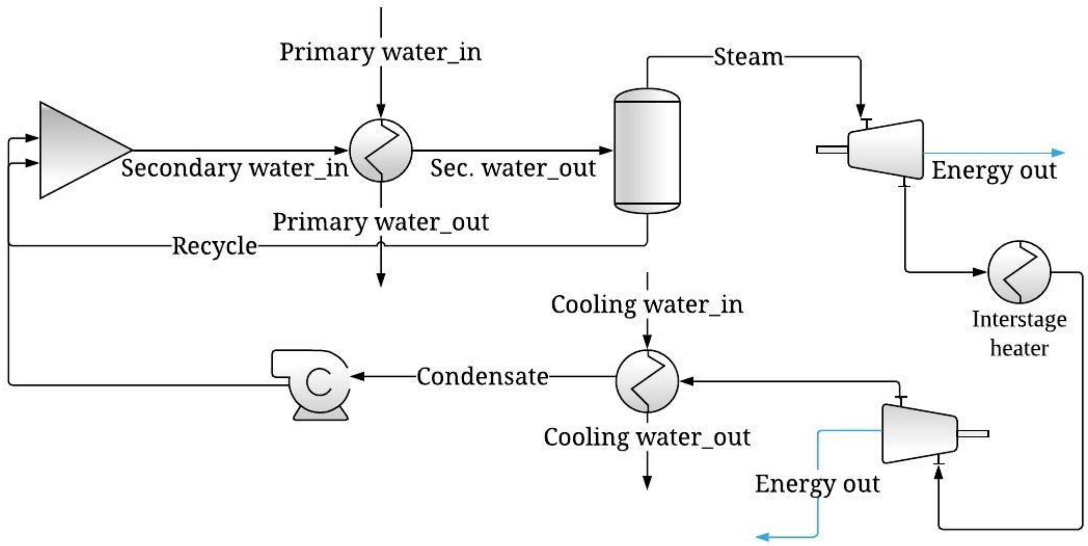

Figure 4: *Aspen plus model of the Company 1 SMR power generation cycle.*

Table 1: *Reactor data for a single unit of the SMR*

Property	Company 1	Company 2
Power output (MWe)	100	225
Capital Cost (millions of $)	300	1350
Area requirement (m^2)	21000	61000
I_t (Max. no. of units in a site)	12	6
Cooling water requirement (TPH)	2000	2200
Multiple unit integration	Yes	No

4.3 Results and Discussion

The model requires a variety of data pertaining to the geographic features of a location. Some of this information was obtained from the public domain and when it was not available suitable approximations were made. The population in the neighbourhood area of a site was assumed as the sum of the population in the load points around the site which fall within the neighbourhood radius of the SMR. The population in a particular load point was assumed as a function of their power demand and area. The distance to the nearest cooling water source was approximated as the distance to the ocean since Jurong is a small island. Since Singapore is located in a relatively safe seismic zone the earthquake risk factor was not considered.

The model has been implemented in a smart system called the J-park simulator (JPS). It uses an ontology based knowledge base to manage information relevant to an EIP. The required data is taken from these knowledge bases and fed to the model. In the current version, the model considers data pertaining to 28 potential sites and 179 load points. This data is presented in the appendix section of the paper. It is executed using the baron

Table 2: *Reactor properties of Company 1 SMR used in Aspen modell.*

Reactor pressure	155 bar
Steam pressure	60 bar
Primary Water Outlet Temperature	297^{o}C
Turbine is-entropic efficiency	0.8
Turbine mechanical Efficiency	0.4

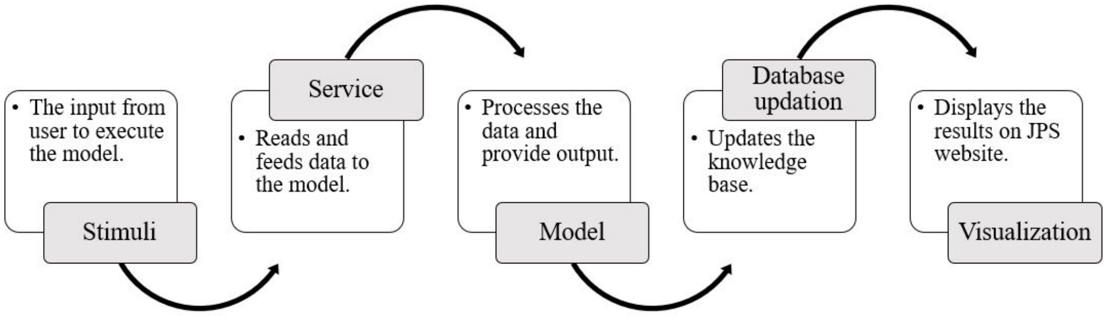

Figure 5: *The proposed architecture for model execution in JPS.*

solver in GAMS. After execution, the model gives the geographic locations of the chosen locations along with their required capacities and reactor types. These are then visualised on a Google map and are made available online. The entire process is automated using a series of agents and a brief overview of the process is shown in figure 5.

Figure 6 and Table 3 shows the model results for the first model run wherein all the concerned factors are considered. It can be seen that only the Company 1 reactors were chosen and the model heavily favours placing maximum units at a chosen site. This can be attributed to the dominating capital cost function which shadows the other factors considered in the model. The capital cost benefit from SMR integration in Company 1 SMRs tipped the model in its favour.

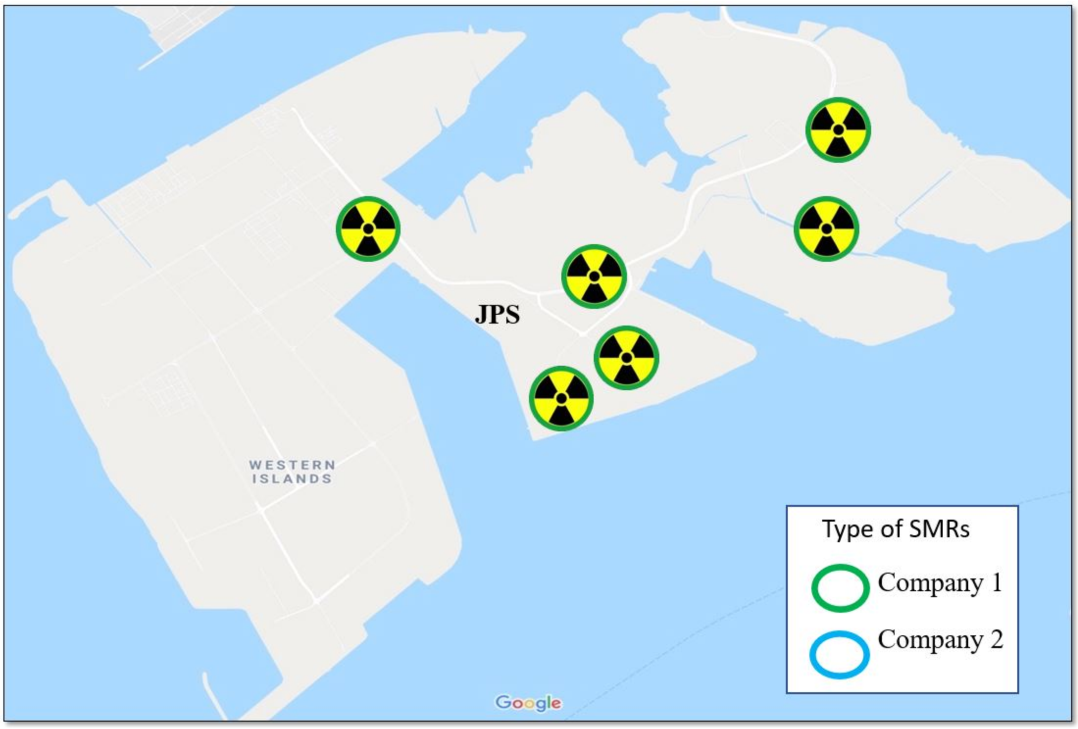

Figure 6: *First run with all objectives given equal consideration.*

Table 3: *SMR network results for first run (All costs are in millions of USD/year)*

Sl.No.	t	i	F_{it}(MW)	C_s	PC_s	RN_s
1	Company 1	12	600	134	.07	.16
2	Company 1	12	600	134	.02	.13
3	Company 1	12	600	134	.03	.18
4	Company 1	12	600	134	.15	.2
5	Company 1	6	300	74	.17	.10
6	Company 1	12	600	134	.12	.21

Figure 7 and Table 4 shows the model results when effect of the capital cost function is not considered. This greatly reduces the advantage of having more number of units at a place although the effects of cooling water pipeline cost and neighbourhood risk might come into play. The results show that Company 2 reactors are chosen with a couple of locations with a lower number of SMR units but still not many sites are chosen. This model run requires significant time for reaching an optimum because all annualised cost functions are of the same order. Also, a slightly different optimum was observed when the initial conditions to the solver were changed.

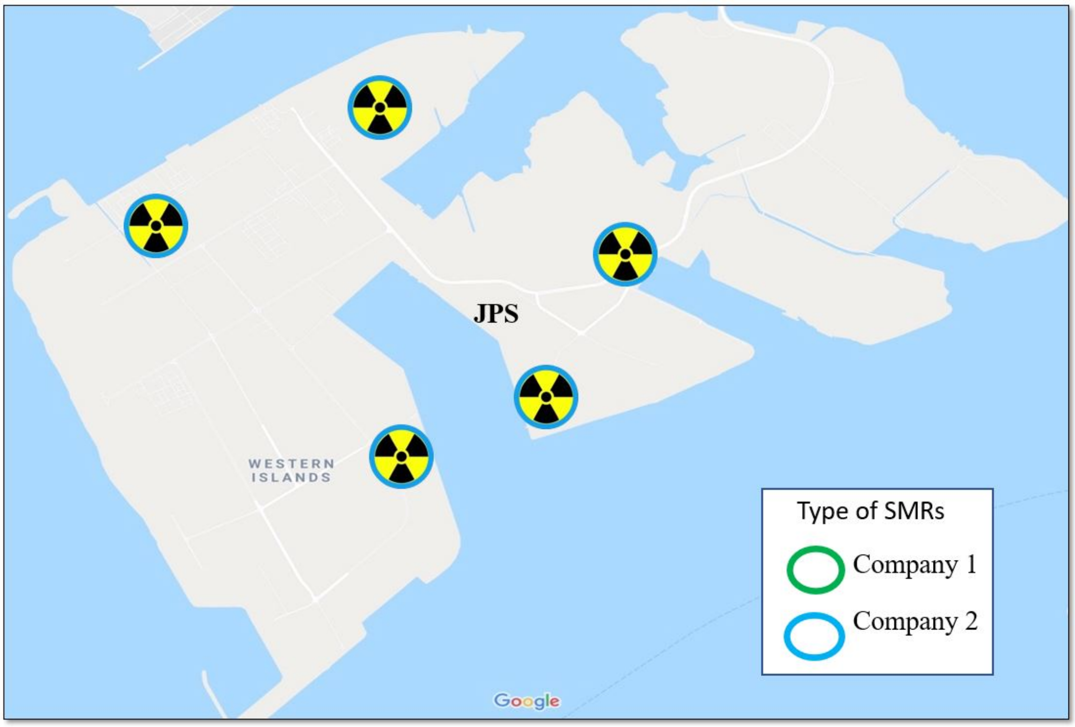

Figure 7: *Second run where capital cost is not considered.*

Table 4: *SMR network results for second run (All costs are in millions of USD/year)*

Sl.No.	t	i	F_{it}(MW)	C_s	PC_s	RN_s
1	Company 2	6	1350	361	.07	.08
2	Company 2	6	1350	361	.11	.12
3	Company 2	1	225	60	.02	.02
4	Company 2	1	225	60	.15	.08
5	Company 2	1	225	60	.027	.12

Figures 8 and Table 5 shows the model results when only the cooling water pipeline cost is considered. It can be seen that the model results favour the Company 2 design because of its significantly lower cooling water requirements per MW of power generated. It is also interesting to note that the model has skipped some locations closer to the cooling water source than the selected location because of the larger area requirement for this type of SMRs. The cooling water cost function also favours placing maximum units in a site as is evident from the results. This is because it is cheaper to build a larger pipeline than to construct a new one.

Figure 9 shows a zoomed in version of the model visualisation available in the JPS website wherein a user clicks on a particular plant and it displays information regarding that plant.

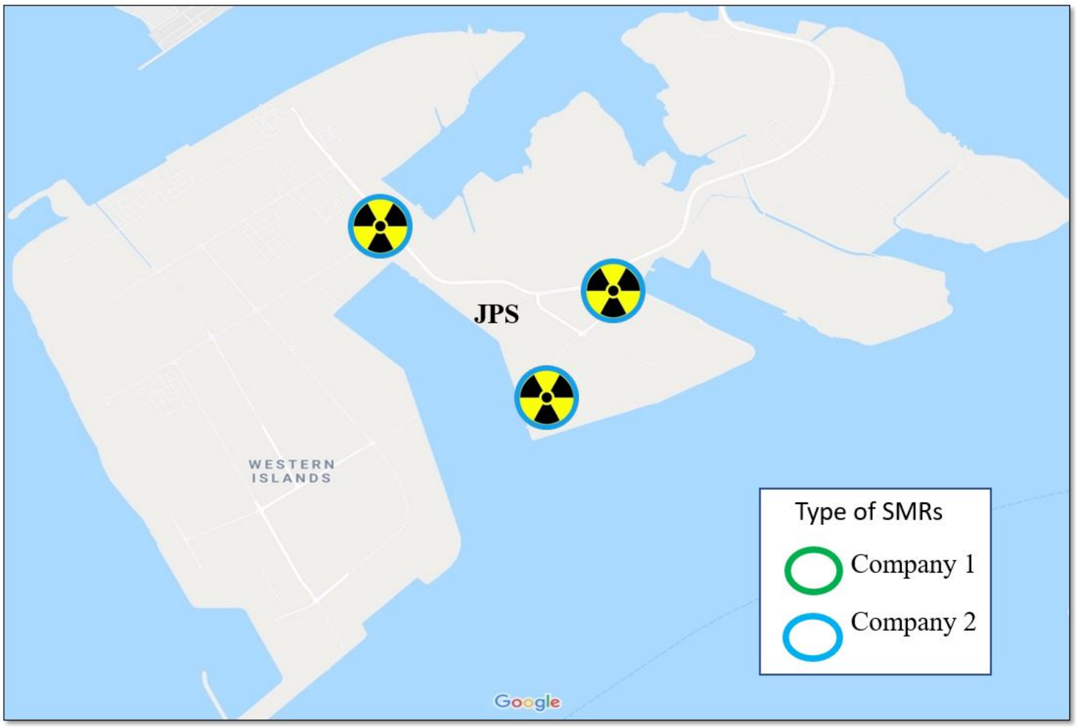

Figure 8: *Run 3 when only pipeline cost is considered*

Table 5: *Results for run 3(All costs are in millions of USD/year).*

Sl.No.	t	i	F_{it} (MW)	PC_s
1	Company 2	6	1350	.07
2	Company 2	6	1350	.02
3	Company 2	3	675	.06

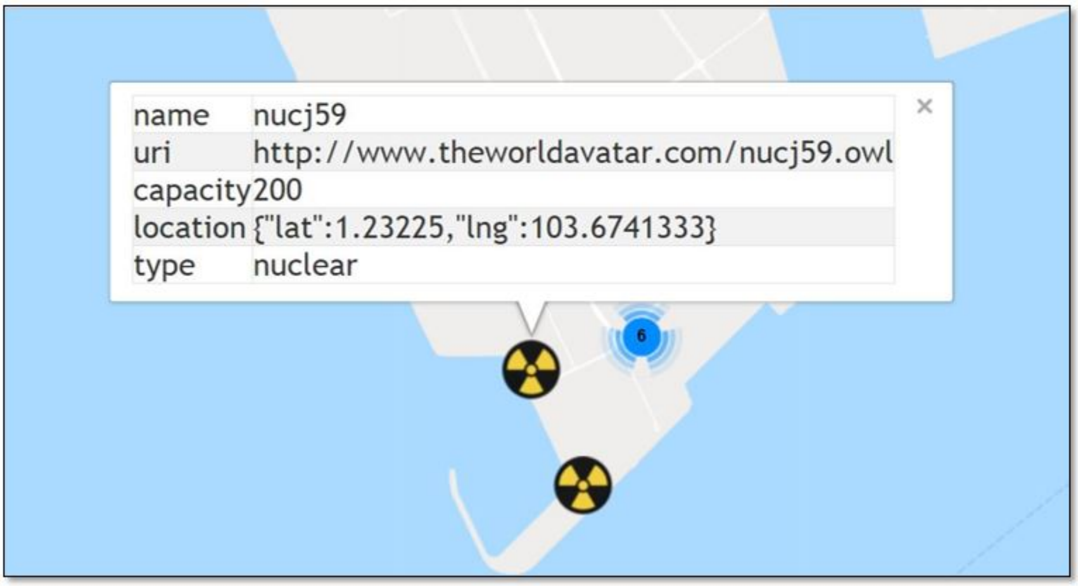

Figure 9: *Visualisation of the model in JPS*

JPS has an approximate peak demand of 3.3 GW. Meeting this demand requires an overnight capital cost of around 16.5 billion USD or an annualised capital cost investment in the tune of 850 million $\$/year$ for 20 years which is a major commitment. Assuming a variable cost of around 5 $cents/kWh$, a capacity factor of .9, fixed operations and maintenance cost of 15 $\$/MWh$ and fuel cost of 5.76 $\$/MWh$ [29], the simplified Levelised Cost of Energy (LCOE) for the SMR network comes around to 52 USD/MWh which is significantly higher than the present cost of energy but comparable to the LCOE for large nuclear power plants. The cost of decommissioning the plants and waste disposal have not been included in our analysis. Another major factor that needs to be considered will be the reduction in capital cost as the SMR technology becomes more established. Unlike large nuclear power plants SMRs can be factory made and as the technology becomes more matured, the cost of production will reduce significantly.

5 Conclusions and future works

A quantitative evaluation model capable of ranking potential sites for its suitability of having a modular NPP network is proposed in the paper. The model requires geographical and energy demand data from a region for its execution. It does not require any qualitative data and hence can be easily scaled up provided the required data is available. This attribute makes the model a successful preliminary analysis tool upon which further studies could be carried out.

A case study was conducted on the JPS to study the effectiveness of the model. The results from the case study show that such a scenario is feasible but it requires successful tackling of the challenges mentioned in the paper. The first and foremost setback is the lack of commercially tested technology. The modular nuclear technology is still in its nascent stage and even though there are many designs from trusted companies, none of them has been deployed commercially. This could change in the coming years as there are many projects in various stages of development across the globe. Another factor is the prohibitive cost and losses in converting the existing energy infrastructure to match the new requirements. Singapore, being a nation with a strong economy can afford the cost but there needs to be a proper plan on how to deal with the existing infrastructure. Finally, the public and political perception about nuclear technology in general, has to change for any significant step to be taken towards a nuclear powered future. This will require increasing awareness about nuclear power and strong political will from the government.

The model can be made more effective if it is attached to a smart system that can feed all the necessary data into the model and visualise its output. A preliminary step into this smart system is the JPS, the current version of which is capable of automating the entire process with some limitations. The present model considers modular reactor technology as the sole source of energy. A hybrid model which takes into account multiple green sources of energy like nuclear, solar, wind and biomass can yield better results.

Acknowledgements

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List of abbreviations

NPP	**N**uclear **P**ower **P**lant
EIP	**E**co **I**ndustrial **P**ark
MINLP	**M**ixed **I**nteger **N**onlinear **P**rogramming
JPS	**J** **P**ark **S**imulator
SMR	**S**mall **M**odular **R**eactor
PWR	**P**ressurized **W**ater **R**eactor
GAMS	**G**eneral **A**lgebraic **M**odeling **S**ystem

List of symbols

z	Objective function	
p	Load point index	
s	Potential site index	
t	SMR type index	
n_{ts}	Number of power modules of type t in s^{th} site	
d_{sp}	Distance from s to p	m
f_{sp}	Power delivered from s^{th} site to p^{th} load point	

D_p	Demand from p	MW
A_s	Available site area	m^2
σ_p	Population density at p^{th} site	$/m^2$
d_{cs}	Distance from s^{th} site to cooling water source	m
F_t	Capacity of t^{th} type SMR unit	MW
UA_t	Minimum area required for a SMR of type t	m^2
L	Project life span	m
FP	Probability of reactor failure	
EP_s	Probability of occurrence of an earthquake in a year	
PU	Median probability of unacceptable performance	
C_s	Annualised capital cost of all the SMR units at site s	$\$/year$
C_{ts}	Capital cost of all SMR units of type t at site s	$\$$
C_{it}	Capital cost of i units of t type SMR	$\$$
y_{its}	Binary selection variable	
n_{ts}	Number of modular units of type t placed in j	
I_t	Maximum number of SMR units that can be integrated	
t_{sp}	Annual transmission losses arising from power transmission	$\$/year$
α	Distance to loss conversion factor	$\$/mMWyear$
PC_s	Annualised cooling water pipeline cost for site s	$\$/year$
μ_s	Cost per unit length of the pipeline for site s	$\$/m$
D	Discount rate	
r_s	Neighbourhood radius	m
r_o	Neighbourhood radius for SMR unit of $1MW$ capacity	m
RN_s	Neighbourhood risk function for site s	$\$/year$
H	Monetary value of a human life	$\$$
Sc	Cost for replacing secondary equipments	$\$$

Appendix

A.Pipeline cost estimation

The total cooling water flow rate requirement Q_s for a site can be written as:

$$Q_s = \sum_{t=1}^{T} \sum_{i=1} iQ_t \tag{.18}$$

The diameter dr_s required for the cooling water pipeline at site s can be written as:

$$dr_s = \frac{\sqrt{4Q_s}}{\pi v} \tag{.19}$$

where v represents the fluid velocity in the pipeline and is considered to be constant for all the cooling water pipelines. The cost per unit length of a pipeline (μ_s) of diameter dr_s and thickness th can be written as:

$$\mu_s = \pi dr_s th \rho W \tag{.20}$$

where ρ is the density of the pipeline and W represents the cost per unit weight of the pipeline material. Assuming the pipeline to be made of stainless steel with a schedule number of 140 and substituting these values equation (13) is obtained.

B.Potential sites data

Sl.No.	Latitude	Longitude	A_s (m^2)	d_{cs} (m)
1	1.26375	103.70208	1653619	150
2	1.27033	103.71917	408554	225
3	1.2598	103.70175	1118062.9	450
4	1.25338	103.6989	521385.9	50
5	1.2587	103.70395	967515	220
6	1.26612	103.6673	52295.4	2600
7	1.2627	103.67205	58770	1100
8	1.25932	103.67633	22315.3	800
9	1.27782	103.72157	476722.2	370
10	1.26337	103.69822	235159.1	280
11	1.26618	103.67862	147894.1	250
12	1.27012	103.68385	650859	170
13	1.27078	103.6642	68611.7	700
14	1.28147	103.6795	80875.3	375
15	1.25172	103.68468	74749.5	350
16	1.23577	103.68013	32409.7	500
17	1.23465	103.67728	31249.5	450
18	1.272	103.728	55340.8	50
19	1.24548	103.67557	51950.4	2500

20	1.2712	103.67223	39457.1	1750
21	1.25765	103.67243	28878.1	2200
22	1.26022	103.67125	33715.2	2250
23	1.27552	103.67837	246200.2	1120
24	1.24932	103.6848	136758.5	380
25	1.26565	103.66445	47106.6	2050
26	1.27282	103.66413	82154	215
27	1.25622	103.66935	124679.6	2200

C.Loadpoint data

Sl.No.	Latitude	Longitude	A_p (m^2)	D_p (MW)	Population density (m^2)
1	1.29627	103.71158	26326	130	0.00475
2	1.28077	103.7259	55552	6	0
3	1.27948	103.72717	58708	6	0.0024
4	1.27818	103.72848	14506	1	0.00688
5	1.25415	103.7028	17031	2	0.00728
6	1.28203	103.67403	367743	37	0.00772
7	1.28033	103.71897	18630	2	0.00766
8	1.268	103.70397	41517	4	0.00936
9	1.27092	103.68503	31987	21	0.00936
10	1.28033	103.71897	355190	36	0.01283
11	1.268	103.70397	285937	3	0.00977
12	1.27092	103.68503	248262	29	0.00967
13	1.28562	103.72075	207164	25	0.00508
14	1.27463	103.72352	340131	34	0.00718
15	1.27708	103.71325	21465	0	0.00859
16	1.27077	103.71693	30235	3	0.00792
17	1.26755	103.70357	56618	7	0.01158
18	1.26102	103.70023	12050	1	0.01006
19	1.27173	103.68423	30105	3	0.00722
20	1.25062	103.68238	10650	5	0.00548
21	1.26677	103.66602	22110	2	0.00993
22	1.28562	103.72075	107048	3	0.00986
23	1.27463	103.72352	27417	3	0.00507
24	1.27708	103.71325	13406	1	0.00843
25	1.27077	103.71693	97120	8	0.00758
26	1.26755	103.70357	26829	8	0.00641
27	1.26102	103.70023	22153	2	0.00566
28	1.27173	103.68423	26629	3	0.0061
29	1.25062	103.68238	19696	2	0.0128
30	1.26677	103.66602	26412	3	0.00972
31	1.28512	103.72007	28373	3	0.00732
32	1.28318	103.72032	14660	13	0.00495
33	1.2828	103.7195	39376	10	0.00872

34	1.2857	103.72147	7780	7	0.00708
35	1.28623	103.72343	250957	33	0.0074
36	1.2866	103.72088	25002	3	0.012
37	1.2868	103.72033	13157	0	0.00983
38	1.28957	103.71978	11851	10	0.00937
39	1.28858	103.72052	329583	25	0.00496
40	1.28773	103.72088	51216	0	0.00773
41	1.2866	103.72088	114861	0	0.00752
42	1.29025	103.71865	60608	6	0.00696
43	1.28977	103.7176	48662	5	0.00886
44	1.29072	103.7135	15681	2	0.00517
45	1.29117	103.70955	43073	4	0.00608
46	1.29013	103.7111	1292819	1	0.00654
47	1.2751	103.72302	9026	129	0.01128
48	1.27593	103.72225	60636	130	0.00787
49	1.27638	103.72183	33018	130	0.00527
50	1.27715	103.721	34597	3	0.00892
51	1.27927	103.71892	108139	147	0.00726
52	1.27968	103.71925	29682	3	0.00674
53	1.27323	103.722	161959	0	0.00836
54	1.27255	103.72135	99100	10	0.00663
55	1.27198	103.72085	79174	13	0.00585
56	1.2711	103.72002	18313	2	0.01001
57	1.27065	103.72043	18055	2	0.00988
58	1.27058	103.72362	44918	1	0.00831
59	1.27418	103.724	36317	4	0.00901
60	1.27647	103.73005	7371	0	0.00397
61	1.27233	103.73472	13984	1	0.00751
62	1.28048	103.72783	14524	0	0.00822
63	1.279	103.72935	25418	0	0.00664
64	1.27852	103.73172	36738	4	0.0058
65	1.28147	103.72685	13648	1	0.00716
66	1.27745	103.71285	97618	1	0.0089
67	1.2789	103.71182	4709	0	0.01025
68	1.27817	103.71455	132273	10	0.00928
69	1.2778	103.71603	13191	1	0.00967
70	1.27847	103.71725	30661	3	0.00947
71	1.27925	103.71668	81902	8	0.00692
72	1.27638	103.71387	80683	0	0.01099
73	1.27617	103.71347	23644	2	0.00408
74	1.27522	103.71422	29039	3	0.00472
75	1.27297	103.71645	146469	15	0.00719
76	1.27328	103.7157	30366	29	0.00691
77	1.27395	103.71502	92132	11	0.00722
78	1.27628	103.71208	73615	7	0.00502
79	1.27692	103.71133	62705	6	0.00783

80	1.27575	103.71098	10217	54	0.00787
81	1.27477	103.70982	103476	10	0.00522
82	1.27127	103.71513	20827	2	0.00942
83	1.27302	103.71015	31073	3	0.00482
84	1.27062	103.7174	9256	1	0.00428
85	1.26285	103.709	16305	2	0.0096
86	1.26602	103.72735	221493	22	0.00918
87	1.26587	103.7275	15264	2	0.00751
88	1.2669	103.72503	113970	11	0.01093
89	1.26697	103.7165	16618	2	0.00395
90	1.26503	103.71547	34930	3	0.01082
91	1.26337	103.72508	41028	4	0.01004
92	1.2631	103.72477	26140	0	0.00902
93	1.26927	103.70505	25070	125	0.00919
94	1.26993	103.7064	38736	4	0.00604
95	1.2691	103.707	139816	14	0.00578
96	1.26978	103.7086	30531	3	0.00904
97	1.26712	103.70435	10110	1	0.00429
98	1.26532	103.70345	15034	2	0.00842
99	1.26463	103.70372	25290	3	0.0068
100	1.26285	103.709	21082	30	0.00713
101	1.26223	103.70992	99853	43	0.00761
102	1.26167	103.7107	1323804	132	0.00747
103	1.26303	103.70133	871626	0	0.00836
104	1.26285	103.70228	695886	70	0.00537
105	1.26375	103.70208	630741	91	0.00964
106	1.2636	103.70292	909539	91	0.00809
107	1.26458	103.7022	24942	2	0.01218
108	1.26033	103.70092	55623	9	0.00727
109	1.2598	103.70175	90640	9	0.00693
110	1.25647	103.70152	39795	19	0.0058
111	1.25335	103.70233	28177	3	0.0131
112	1.25905	103.70318	60976	11	0.0117
113	1.2587	103.70395	105752	3	0.01017
114	1.25932	103.7044	96225	10	0.01225
115	1.25813	103.70538	86659	9	0.00942
116	1.25832	103.70653	288368	9	0.00951
117	1.25828	103.70663	102203	0	0.00541
118	1.25822	103.70677	20238	20	0.00695
119	1.26618	103.67862	10069	58	0.00597
120	1.26262	103.68	42216	4	0.00419
121	1.26007	103.6994	226566	63	0.00832
122	1.25935	103.6981	45516	0	0.00578
123	1.25893	103.69852	73412	0	0.00987
124	1.25463	103.69857	298728	30	0.00341
125	1.25338	103.6989	33924	65	0.00667

126	1.25343	103.69733	569902	57	0.00586
127	1.26193	103.69887	114909	54	0.00661
128	1.26253	103.6992	149151	15	0.00722
129	1.25985	103.69457	92905	0	0.00905
130	1.26337	103.69822	89269	9	0.00697
131	1.2631	103.69718	153401	39	0.00741
132	1.26167	103.69507	303749	30	0.00449
133	1.26527	103.6946	836516	39	0.00846
134	1.26673	103.68975	344666	8	0.00566
135	1.27012	103.68385	79015	65	0.00689
136	1.26958	103.68318	908988	47	0.01325
137	1.27035	103.68267	237635	47	0.00801
138	1.26973	103.68175	300874	0	0.00713
139	1.2687	103.68205	101321	0	0.00883
140	1.2682	103.67123	172123	0	0.00699
141	1.27552	103.67837	322874	0	0.00655
142	1.27408	103.67443	124425	0	0.00719
143	1.27693	103.67675	66302	7	0.00925
144	1.2789	103.6754	319377	0	0.00843
145	1.27968	103.67368	121852	0	0.00623
146	1.28225	103.6779	54780	0	0.00844
147	1.28285	103.67593	53978	63	0.01246
148	1.28147	103.6795	82850	0	0.01022
149	1.28123	103.68015	9988	1	0.01131
150	1.28733	103.68372	39904	0	0.00595
151	1.25172	103.68468	508076	51	0.00705
152	1.25193	103.68557	52973	5	0.00791
153	1.24932	103.6848	10288	11	0.00674
154	1.24415	103.68575	98048	11	0.00827
155	1.24348	103.6867	75952	63	0.00829
156	1.24195	103.68607	149777	141	0.00772
157	1.23673	103.67957	78316	0	0.0102
158	1.23577	103.68013	249160	0	0.00866
159	1.22593	103.67698	85054	9	0.01005
160	1.23412	103.67802	153256	0	0.00854
161	1.23465	103.67728	20686	9	0.00729
162	1.2328	103.67577	130453	38	0.01035
163	1.23363	103.67553	113684	38	0.0105
164	1.23225	103.67413	152175	15	0.01127
165	1.2528	103.67472	141921	14	0.00772
166	1.24548	103.67557	60550	0	0.00951
167	1.24453	103.6759	189661	0	0.00771
168	1.24533	103.67333	435275	12	0.00789
169	1.24638	103.674	64465	0	0.00792
170	1.26665	103.66453	114145	0	0.00904
171	1.26565	103.66445	34038	0	0.00786

172	1.26887	103.66567	626913	0	0.00623
173	1.27078	103.6642	124156	12	0.00668
174	1.27135	103.66213	52742	50	0.00575
175	1.2705	103.66242	78046	0	0.00388
176	1.27082	103.66132	98502	10	0.00847
177	1.27282	103.66413	17597	21	0.00521
178	1.27507	103.66717	26881	3	0.0099
179	1.27722	103.67008	32468	3	0.00636

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