Optimal Geographical Distribution of Small Modular Nuclear Reactors in France

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January 2024

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1 Introduction

In the past years, the research on nuclear energy have not been stopped, and has conducted scientists to discover new possibility of application and energy production. The latest technology is a new form of reactor, which is smaller than the existing ones, they are called Small Modular Reactors (SMRs). They offer scalable and efficient energy generation. The possibility of having decentralized energy production is an interesting scenario for the future development of the energy production and distribution sector. The main goals, that scientists have set and reached regarding this technology are: scalability, safety, efficiency and low environment impact.

Scalability is a really interesting goal. As a matter of fact, the actual operating plants are of massive dimensions nowadays. They produce great amount of energy and they have to be located far away from where the energy is needed since the plants have really specific needs in terms of safety and resources. For this reason, scalability was a really interesting goal to be achieved. The possibility of having smaller production plants, located closer to the locations where the energy is actually needed has also on impact on the energy lost during transportation.

Another aspect studied and developed was the enhancing of safety. Bigger plants could lead to, potentially, greater disasters. The SMR technology has been developed to be safer, since in every plant are present less radioactive materials and the reaction can be controlled easier. Safety plays a really important role when it comes to the development of new technologies, since it has been internalized the amount of damages that incidents in nuclear plants can cause.

The nuclear fusion reactions performed inside the SMRs has been improved, compared to the old plants: the efficiency has grown. The fact that the plant is smaller allows a higher temperature and pressure. Thus, an enhanced energy production with a lower amount of row materials needed.

In addition, the general environmental impact of these plants is lower than the old ones. As a matter of fact, the optimized process of fusion needs less uranium, can process it more, meaning a greater energy production for the same amount of the raw material, and the actual time needed for the nuclear waste to become non radioactive again is lower. It is a win-win situation with both enhanced energy production, reduction of the amount of waste, and reduction of the time this waste needs to be stored safely.

France is now facing new challenges in the development of new policies to face the climate changes. The goal set is high and the energy production has to swift rapidly to new, more sustainable sources. This is a collective effort, made by all the Nations to try to slow down the climate changes without reducing the energy production, still allowing for economical development and growth. This collective effort is reflected in Europe by the many initiatives promoted by the European Union, that has set some ambitious goals for its members. The United Nations have also been working really hard and have set the 2030 Agenda in order to spur its member to develop their activities in a more sustainable way. As a matter of fact, many goals are related to energy production in a more affordable and clean way. Not to be forgotten are also the important goals set at a global scale by the COP26 and COP28, that the French government has subscribed and has to achieve.

The French government is, thus, looking for new sustainable energy production sources. It has always relied on the nuclear energy plants; however, the deployed technology is now becoming outdated. As a matter of fact, now in France there are 58 nuclear reactors distributed in 19 plants. The newest plants are now almost twenty years old, but there are also plants from the 1970s still in operation. These plants need to have greater maintenance and some of them need to be dismissed. For this reason the french government is now approaching this new technology of the SMRs.

2 Scope and mission

The objective of this analysis is to provide a detailed analysis of the the possible location for the new SMR in the French Nation. To achieve this goal, the team will be collecting data from the greatest players in France from the energy production and transportation sectors. In a first step, it will be necessary to define the constraints in the location of the reactors. Secondly, the actual evaluation will follow. In the end, a detailed report will be presented showing the action plan. The main assumptions behind this analysis are that the SMR technology will reduce the environmental impact of the energy production, reduce costs of maintenance, and increment job opportunities in the energy production field in the country.

3 Methodological Approach

The project will be developed from various perspectives to provide a clear and effective overview of the potential developments of this technology in the French energy sector. The main goal is locating the new reactors in locations that will match with social, geological and economical perspective. For this reason, it will be developed following these outlined areas.

3.1 Sociological analysis

The sociological analysis will be conducted by the team in order to identify the cities in which it would be easier to set the SMRs. As a matter of fact, the location of a new nuclear plant can be seen in a hostile way by the population, which can easily protest against. The main goal is to outline a map of the general feeling towards the possibility of building these plants in areas where nowadays, no such infrastructure exists. A well developed social study will provide a good starting point for the selection in the second part. The team will take as a starting point some studies that are already published, which are really promising, since they show that most of the French population thinks that nuclear energy is an essential asset for the country. [5]

However, besides assessing the data collecting strategies of this studies and the considered samples, the team would engage with the local authorities, administrations and entities on a regional level. This phase will be characterized by many workshops and focus groups to better outline the situation. This direct connection with the local authorities will also increase trust in the project and it will spread awareness of the considerable benefits deriving by the deployment of this technology. As an output of this phase we expect to create some important graphical representation of the general sentiment of the French population, as it is possible to observe in Figure 1.

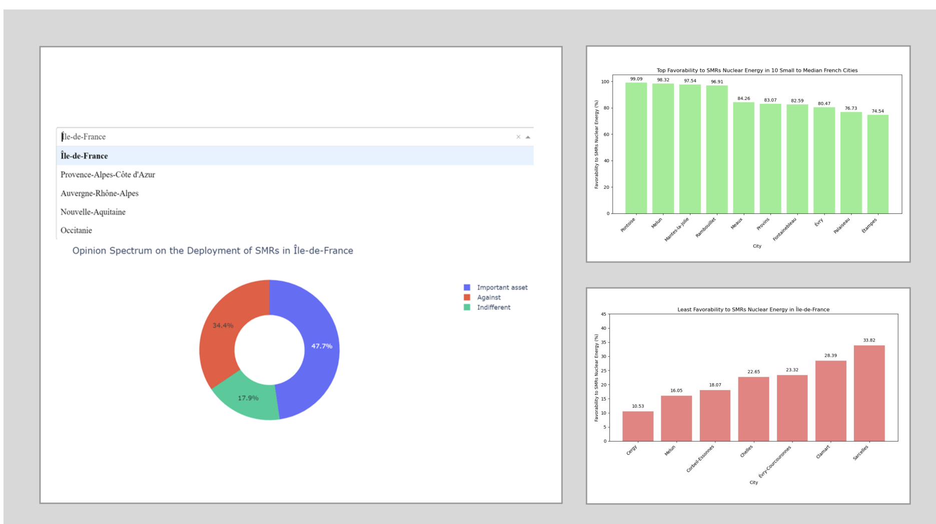

Figure 1: General sentiment towards new nuclear plants [3]

The last phase for the team for the sociological analysis will be centered in the creation of a possible editorial plan to raise awareness in the selected cities. The goal of this editorial plan is to be tailored to the needs and concerns of the population of different areas, while also formulating an approach at a national level. For this reason, the team will be required to travel frequently to the different locations to collect information and get to know the situation under the perspective of outlining the awareness campaign. This output is going to be especially useful when the SMRs are going to be effectively deployed and built, in order to be prepared to operate also on the communication side.

3.2 Econometric prediction

The econometric evaluation will be centered on creating prediction of future of energy demand. It is extremely important to be able to predict how the demand of energy is going to change in the future, covering peaks and trends. It is important to keep in mind that, especially in the first phase, the new SMRs are going to substitute the actual nuclear plants that have been active in the past decades, so they have to produce at least what is already produced by 19 of the current functioning plants. In the future, more modular reactors could be deployed. Thanks to their modular form, they could be built faster and on-site.

Going back to the econometric prediction task, two very different models will be applied to produce the output: the ARIMA model and a recurrent neural network with Long Short-Term Memory. They are both powerful methods to predict future behaviors of a variable of interest, in this case the energy demand, but they have a very different structure and utility. On the one hand, The ARIMA model is fast to compute and needs only values related to the actual time series of energy demand on the past, while the RNN with LSTM can consider as input features some macroeconomic, environmental, and demand and supply time series.

The Autoregressive Integrated Moving Average (ARIMA) model combines autoregression, differencing, and moving averages to make predictions, and is going to portray a first prediction of the energy demand. Due to its structure, it is easier and faster to obtain. The model takes into consideration all the past periods for which there are observations and, taking seasonality into consideration, tries to predict the future behavior of the variable of interest. ARIMA models are effective capturing and forecasting patterns for time series data, which is the first goal of this econometric analysis.[1]

The model is structured as follows:

$$Y_t = c + \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \ldots + \phi_p Y_{t-p} - \epsilon_t - \theta_1 \epsilon_{t-1} - \theta_2 \epsilon_{t-2} - \ldots - \theta_p \epsilon_{t-p} \tag{1}$$

The parameters $c, \phi_1, \phi_2, ..., \phi_p, \theta_1, \theta_2, ..., \theta_p$ are estimated during the model fitting process.

- Y_t is the observed value of the energy demand at time t
- c is the constant term
- $\phi_1, \phi_2, ..., \phi_p$ are the autoregressive coefficients
- ϵ_t is the white noise error term at time t
- $\theta_1, \theta_2, ..., \theta_p$ are the moving averages coefficients

In this way the model is able to capture the temporal dependencies, trends and seasonality.

On the other hand, Recurrent Neural Networks (RNNs) are a type of neural network architecture designed to effectively process sequential data by maintaining a memory of past inputs. The great advantage of RNNs, is that they can consider also past data of other variables when making the prediction and are able to discover hidden relationships between the variable of interest and the other dependent variables. This kind of models are very useful when it comes to processing panel data for a big amount of observations. However, they might have some difficulties since they do not ponder the weight proportionally to the distance in time. For this reason, the model will be developed with Long Short-Term Memory units, which are cells with input, output, and forget gates. They each contribute to control flow of information within the network. The input gate regulates the flow of new information into the memory cell, the forget gate manages the retention or removal of existing information, and the output gate controls the information flow from the memory cell to the next time step. This gating mechanism enhances the model's ability to capture and retain relevant information over extended sequences. As a consequence, the RNN with LSTM units excels at learning and leveraging temporal dependencies, allowing it to capture intricate patterns and relationships in sequential data. Given the great prediction power of this machine learning method, the time needed to train such a model is considerable. For this reason, a first draft of the energy demand will be predicted with the ARIMA model and only in a second time the result of this model will be of interest.

Both models will be trained and tested to give prediction for the Nation as a whole, but also for individual cities in order to offer a tailored description of the future dynamics of the energy demand on different levels.

The data needed to create these models, are already collected by many public entities around France. As a matter of fact, for the ARIMA model, only data regarding the energy demand in the past will be needed. This kind of data are collected hourly by RTE and will have a central role on the estimation of the future behavior of the demand. For the training of the RNN, information from many other sources will be needed. However, when it comes to population growth and macroeconomical indicators, the Government and the INSEE are always publishing their researches. These data are going to be especially useful since there are not just past data, but also predictions of their future development. In addition, these entities have to respect international standards when it comes to their data collection processes and data elaboration. As a consequence, the resulting data are characterized by their high quality and usability. [4]

3.3 Locating the plants

The main task of this analysis will be to select the most suitable location for the SMRs. This evaluation is based on many parameters. As a matter of fact, all the data collected by the team on sociological aspects and the prediction for the development in energy demand are going to be vital in the resolution of this task. Other data, regarding the population, should be already available due to the previous phases. For the actual distribution of the plants, the team needs to collect data regarding the energy infrastructure status in the country, data already possessed by the RTE, and also on the geological features of the country. These data are already available and owned by statal entities such as the BRGM (Bureau de Recherches Géologiques et Minières). All these data will help determining the constraints to the P-median model that is going to be developed.

To determine the best possible solution for setting reactor location, the model implemented is the P-Median algorithm, which is a facility location optimization method. The objective is to strategically place a fixed number (p) of facilities among a set of potential locations (Q) to minimize the overall costs. The problem assumes that there is a demand associated with each location, and the goal is to find the optimal facility locations such that the sum of the distances or costs between each demand point and its assigned facility is minimized. As a result of this minimization algorithm, the result will be a binary variable associated to each city with value 0 if the city is not a good candidate or value 1 if it represents a good location for the setting of the SMR. This resolution technique is extremely powerful when the set of possible facility locations is small, but it becomes computationally impossible as soon as the set of possible solution increases. The number of possible combinations becomes quickly equal to $n!/(Q!(n-Q)!)$, where Q is the group of possible locations and n is the set of cities that need to be served, in this specific case all the cities in France. [2]

As it appears clearly from the the 2:

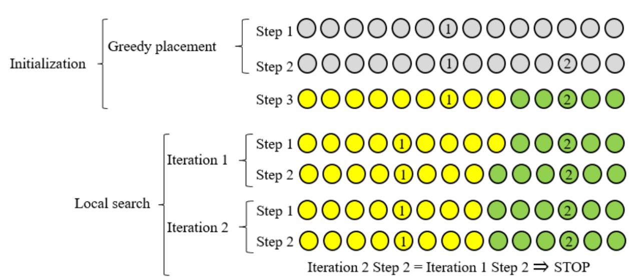

Figure 2: Heuristic algorithm [6]

To overcome this technical and computational issue, there are some strategies to be implemented that allow to reduce significantly the set of possible combinations, while maintaining the presence of all the constraints previously described. These strategies are called heuristic resolution, since they start from a given possible solution and they optimize in the neighborhood. The resulting solution is a local optimum, not the true optimum, but still it is the best reachable solution. Diving a little deeper into the algorithm, it is composed of two phases: the initialization at the beginning and then the local search performed as many times as needed to reach a level in which no change will reduce significantly the cost.

- Initialization phase: the SMRs are placed in a greedy way and then they are associated with the other cities where they provide the energy
- In the local search, at each repetition the locations for the SMRs can be changed and consequently the associated cities. As a matter of fact the obtained solution appears not to be the best one but still it has a great potential and it is feasible.

3.4 Visualization

One efficient way to summarize our results for our audience could be through some visual representations. The idea is also to provide some maps portraying the possible development of the technology and its positioning in the Country. As an example of a little area we can reference Figure 3 that portrays easily the solution. The city in which the plant is located is the red one and the cities depending on its reactor are connected with a blue line.

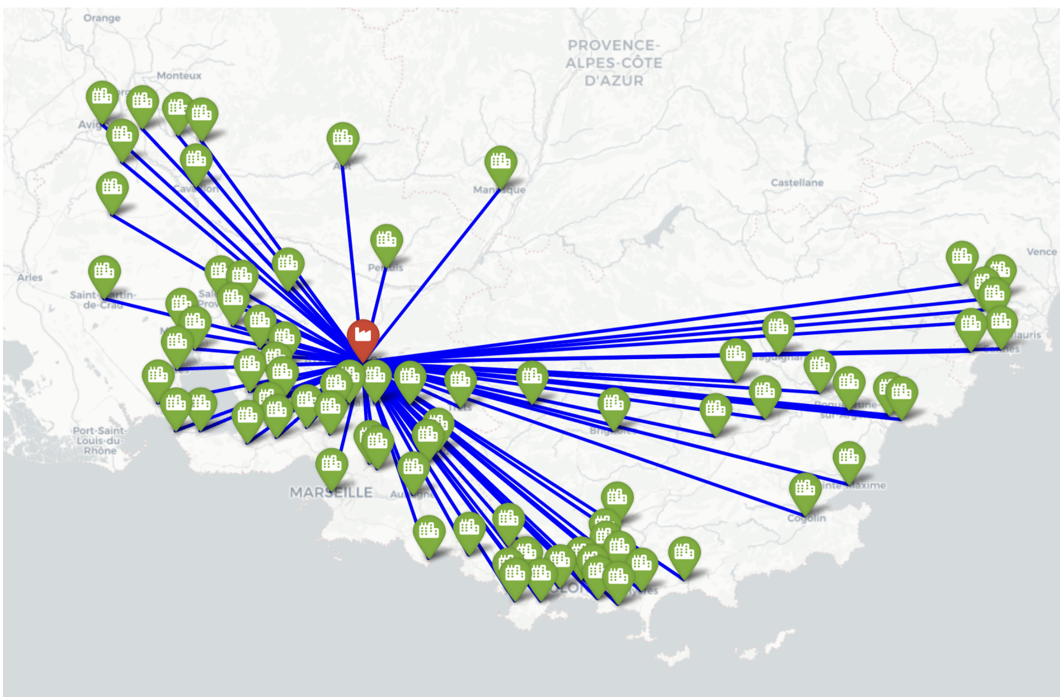

Figure 3: Representation of the results[3]

4 Team Presentation

In order to achieve our goal, we need a multi-skilled team. The team will be made of 6 people: project manager, financial analyst, econometrist, nuclear engineer, communication expert and sociologist. Each member of the team is going to fulfill some specific tasks. All the team will be dependent on the project manager, but all the professional will be on the same level.

Member	Number	Qualification Required	Experience
Project Manager	1	Master in project management or economics	10 years
Financial Anlayst	1	master in finance or in financial related topics	2 years
Econometrist	1	Master in econometrics or statistics	2 years
Sociologist	1	At least a Bachelor in sociology or psycology	2 years
Communication Expert	1	At least a Bachelor in communication or marketing	2 years
Nuclear Engeneer	1	Master in Nuclear Engeneering	5 years

Figure 4: Team description

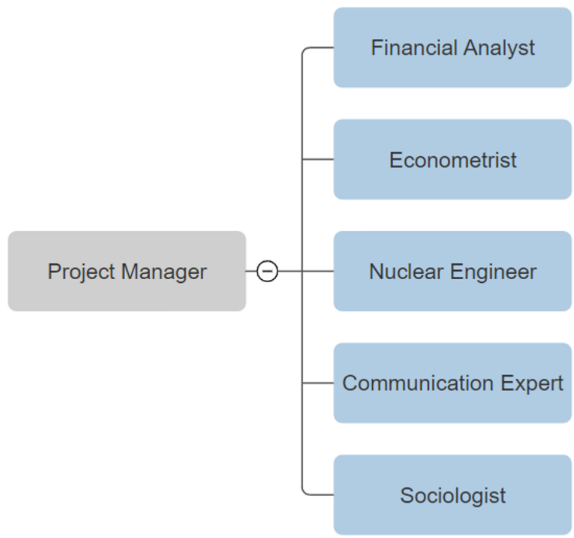

Figure 5: Organigram for the Project [3]

5 Description of the Work Plan

We have organized our working plan following these four phases:

Phase 1 : Project Inception and Stakeholder Meetings (9 weeks)

- Gather information on existing infrastructure, population density, and environmental factors: Collect relevant data to inform the decision-making process. This includes information on existing energy infrastructure, population distribution, and environmental considerations. (3 weeks)

- Engage with government agencies, environmental organizations, and local communities: Initiate discussions with key stakeholders to understand their perspectives, concerns, and expectations. This will involve meetings with government representatives, environmental organizations, and members of local communities. The goal is to build a shared understanding of the project and gather initial feedback. (6 weeks)

Phase 2: Data Collection and Analysis (25 weeks)

- Gather information on existing infrastructure, population density, and environmental factors: Collect relevant data to inform the decision-making process. This will include information on existing energy infrastructure, population distribution, and environmental considerations. (8 weeks)

- Continue gathering data, ensuring comprehensive coverage: Conduct a thorough and comprehensive data collection process, ensuring that all relevant aspects for Small Modular Reactor

(SMR) placement are considered. This will involve collaborating with various agencies, accessing existing databases, and conducting surveys or studies. (8 weeks)

- Utilize advanced modeling techniques for preliminary analysis: Employ advanced modeling techniques to analyze the collected data. This analysis will include predictive modeling for energy demand, economic assessments, and environmental impact assessments. The goal is to obtain preliminary insights into potential SMR sites. (9 weeks)

Phase 3: Feasibility Assessment (34 weeks)

- Evaluate the technical feasibility of potential sites for SMR deployment: Assess the technical aspects of potential SMR sites, considering factors such as geological conditions, infrastructure compatibility, and safety measures. (10 weeks)
- Assess the economic viability of SMRs in selected locations: Conduct economic assessments to evaluate the financial feasibility of deploying SMRs in selected locations. Consider factors such as construction costs, operational expenses, and potential economic benefits. (9 weeks)
- Evaluate and mitigate environmental impacts of chosen sites: Assess the environmental impact of deploying SMRs and develop strategies to mitigate any adverse effects. This will involve considering the impact on local ecosystems, water resources, and air quality. (8 weeks)
- Engage in ongoing collaboration with local communities: Maintain open communication with local communities throughout the feasibility assessment phase. Address concerns, gather continuous feedback, and involve community members in the decision-making process. (7 weeks)

Phase 4: Recommendation and Reporting (7 weeks)

- Compile detailed reports on technical, economic, and environmental aspects: Summarize the findings from the feasibility assessment in comprehensive reports. Provide detailed information on technical, economic, and environmental considerations to support decision-making. (4 weeks)
- Present results of the assessment to relevant stakeholders: Share the assessment results with key stakeholders, including the Electricity Transmission Network and the Ministry of Ecological Transition. Present the information in a clear and accessible manner, addressing any questions or concerns. (2 weeks)
- Deliver a presentation summarizing the findings and recommendations: Create a presentation that highlights the key findings and recommendations from the assessment. This presentation serves as a tool for conveying the results to a broader audience, including decision-makers, the public, and other stakeholders. (1 weeks)

6 Financial Proposal

Names	Position	Nb of days	Daily fees	Total
Project Manager	Head of the project	70	700	49000
Financial Anlayst	Expert in energy demand	180	500	90000
Econometrist	Expert in modellisation	180	500	90000
Sociologist	Expert in social dinamics	111	300	33300
Communication Expert	Expert appropriate interaction	41	300	12300
Nuclear Engeneer	Expert in nuclear plants	100	500	50000
Total		**682**		**324600**

Item No	Description	Quantity(days)	Unit price (€)	Total amount
	Travel fees for project manager			
1	Allowance	52	50	2.600
2	Transportation	52	80	4.160
3	Accommodation	52	50	2.600
	Travel fees for sociologist and commuication expert			
1	Allowance	35	100	3.500
2	Transportation	35	160	5.600
3	Accommodation	35	100	3.500
	Travel fees for econometrist, financial expert			
1	Allowance	30	100	3.000
2	Transportation	30	160	4.800
3	Accommodation	30	100	3.000
	Travel fees for nuclear engineer			
1	Allowance	51	50	2.550
2	Transportation	51	80	4.080
3	Accommodation	51	50	2.550
	Other fees			
4	Meetings with local communities	35	500	17.500
5	Equipements	1	5000	5.000
6	Fixed costs	1	96000	96.000
7				-
8				-
9				-
10				-
11				-
Total				**160.440**

Total project cost

Cost Component	Cost
Staff	364.600
Other expenses	160.440
Overheads (10%)	52.504
TOTAL	577.544

Figure 6: Project Budget

References

[1] Jason Brownlee. Sarima for time series forecasting in python, 2022. Accessed: September 16, 2024.

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[3] J. Velasco F. Nardin, S. Villamil. Own elaboration with simulated data, 2022. Image created by the author with simulated data.

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[5] Orano. According to a bva study for orano: Most french people think nuclear energy is an asset for france's energy independence, 2019.

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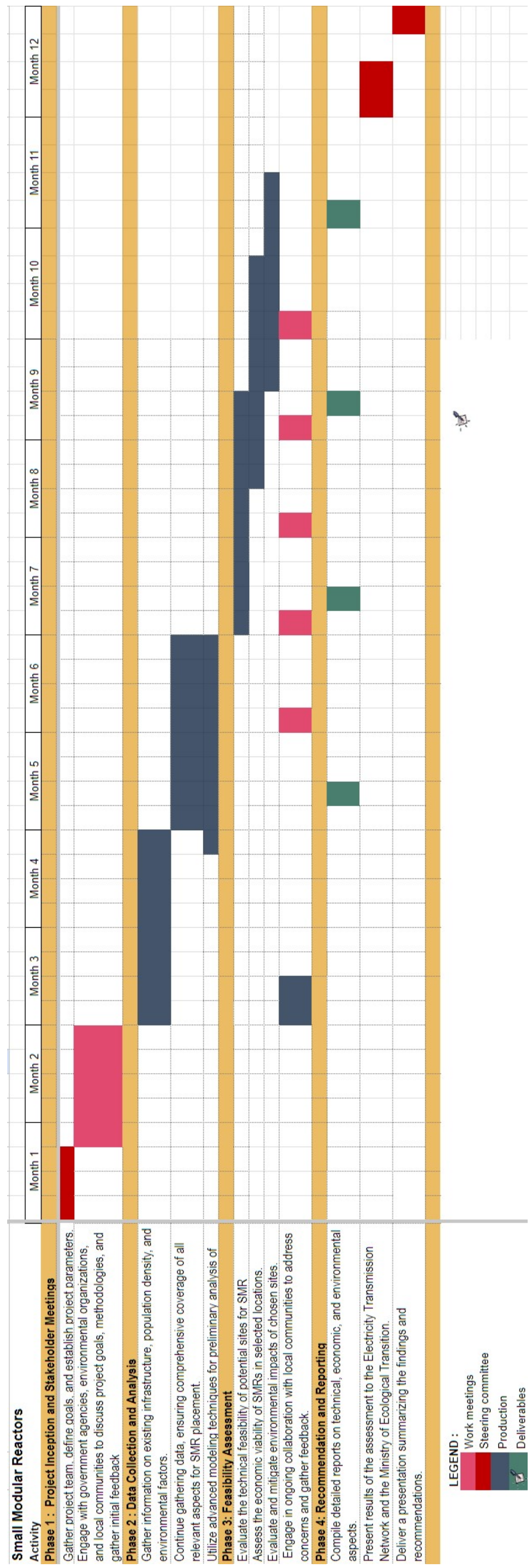

Figure 7: Project timeline with phases