Methodology For The Identification Of Sites For The Deployment Of Small Modular Reactors (Smrs) In Slovenia

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ABSTRACT

Achieving long-term security of electricity supply with low carbon intensity is a central policy objective in Slovenia, particularly in light of the ongoing phase-out of fossil fuels and the constraints associated with renewable energy sources **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**. Small modular reactors (SMRs) appear in this context as a promising technological solution due to their modularity, smaller spatial footprint and greater flexibility compared to large nuclear power plants **Error! Reference source not found.**.

Regardless of the advantages, their placement in space requires a comprehensive and systematic approach that takes into account technological, environmental, spatial and safety aspects. The paper presents the methodology used for the early identification of potential SMR locations in Slovenia, which is based on a multi-stage analysis of potentially suitable spatial areas. The methodology used is based on the guidelines of the International Atomic Energy Agency (IAEA) **Error! Reference source not found.Error! Reference source not found.** but is adapted to Slovenian conditions, especially with regard to the limited availability of detailed data in the field of site safety verification for nuclear facilities.

The methodology used is based exclusively on publicly available spatial data, which enables transparency and repeatability of the analyses, but also implies a limitation in terms of their accuracy. The methodological approach involves the implementation of three consecutive phases: suitability analysis, vulnerability analysis and adequacy analysis, followed by ranking of locations. In the first phase, exclusionary technological criteria are used to determine areas where the placement of SMRs is feasible at all. In the second phase, legally defined protection criteria are used to exclude areas where placement is not permissible due to environmental or spatial protection.

In the third phase, the remaining 215 locations are compared with each other based on additional criteria that are not exclusionary, but can significantly affect the feasibility of the project. In the final phase, the locations are ranked using a multi-criteria approach and a uniform four-level scale, which enables transparent comparison and selection of the most suitable locations.

The methodology thus represents a robust basis for the initial spatial analysis and for directing further, more detailed analyses to the most promising areas.

Keywords: *small modular reactors (SMR), siting, suitability analysis, vulnerability analysis, suitability analysis, location ranking, Slowenia*

1 INTRODUCTION

The transition towards a stable, reliable and low-carbon electricity system represents a major strategic challenge for the Republic of Slovenia. As fossil energy sources are being progressively phased out and renewable sources face inherent limitations, the role of nuclear energy as a baseload electricity source is once again coming into focus. In this context, small modular reactors (SMRs) represent a technological option that, due to their modularity, smaller spatial footprint and greater adaptability, could enable a wider range of locations than classic large nuclear power plants.

The placement of SMRs in space remains a demanding process, as despite their smaller size, they are still nuclear and at the same time energy-intensive facilities that require a high level of spatial, safety and technical coordination. Even with smaller nuclear facilities, all requirements of the International Atomic Energy Agenc yas well as all national environmental, spatial and other legislation that affects the placement of nuclear facilities in space, must be addressed at the same time. Experience with the siting of major nuclear facilities in Slovenia, especially in the context of the preparation of expert bases for JEK2, has shown that the key challenges are related to lengthy procedures, demanding coordination of interests in the space, legislative restrictions, dispersed settlement and the lack of data that would be directly useful for the early stages of identifying locations at the national level **Error! Reference source not found.Error! Reference source not found.**.

The paper therefore does not address the final selection of the location for SMR, but rather the methodology of early spatial analysis, the purpose of which is to answer the basic question of where in Slovenia it makes sense to further consider the siting of such facilities. The main goal of the methodology is to use publicly available data to determine areas that meet the basic technological conditions, are not particularly vulnerable from an environmental and spatial perspective, and enable further comparative assessment of the best locations.

2 METHODOLOGICAL FRAMEWORK

The methodology for identifying locations for SMR is based on a multi-stage spatial analysis that allows for a gradual reduction of the area under consideration. This approach is based on the guidelines of the International Atomic Energy Agency (IAEA) and established international practices, according to which wider potentially suitable areas are first identified, and then their suitability is verified in subsequent phases with increasingly detailed analyses. The basic logic of the methodology is therefore a transition from the general to the specific. However, the methodology under consideration cannot be understood as a direct transfer of the IAEA approach to the Slovenian space. The IAEA methodology already in the first phase of site suitability assessment envisages the use of site-specific seismological, geological, hydrological and safety data, as well as detailed field surveys, which are necessary for the final assessment of nuclear safety **Error! Reference source not found.Error! Reference source not found.**. Such data in Slovenia at the level of the entire territory are not systematically collected or are not available in a form that would enable their direct use in early GIS modelling. From the perspective of nuclear safety, the most detailed analyses have been carried out only for the Krško area. For this reason, we have developed an adapted methodology that maintains the phased nature and basic logic of international approaches, but is also adapted to Slovenian spatial and data conditions. Its special feature is that it is based exclusively on publicly available spatial data, which ensures transparency, traceability and repeatability of results, but also represents a limitation in terms of accuracy.

The methodology is therefore suitable primarily for the first phase of spatial analysis, but not for a final assessment of the nuclear safety of an individual location. The approach used has several advantages. It allows for a uniform treatment of the entire territory of the country, comparability of results between locations and clear identification of the main limiting factors. The disadvantages of the methodology used are the dependence of the reliability of the results on the quality of the input data. The spatial resolution of some of the data used is suitable only for a regional and not for a detailed assessment of the location, therefore such an approach represents an appropriate professional basis for the initial orientation of further analyses to those areas where further study is meaningful. The methodology consists of the following substantive steps: suitability analysis, vulnerability analysis and adequacy analysis, followed by location ranking. In the first step, areas that do not meet the basic technological conditions are eliminated. In the second step, areas with significant environmental, spatial or safety constraints are eliminated. In the third step, the remaining locations are compared with each other according to additional criteria that enable the identification of key challenges of each location.

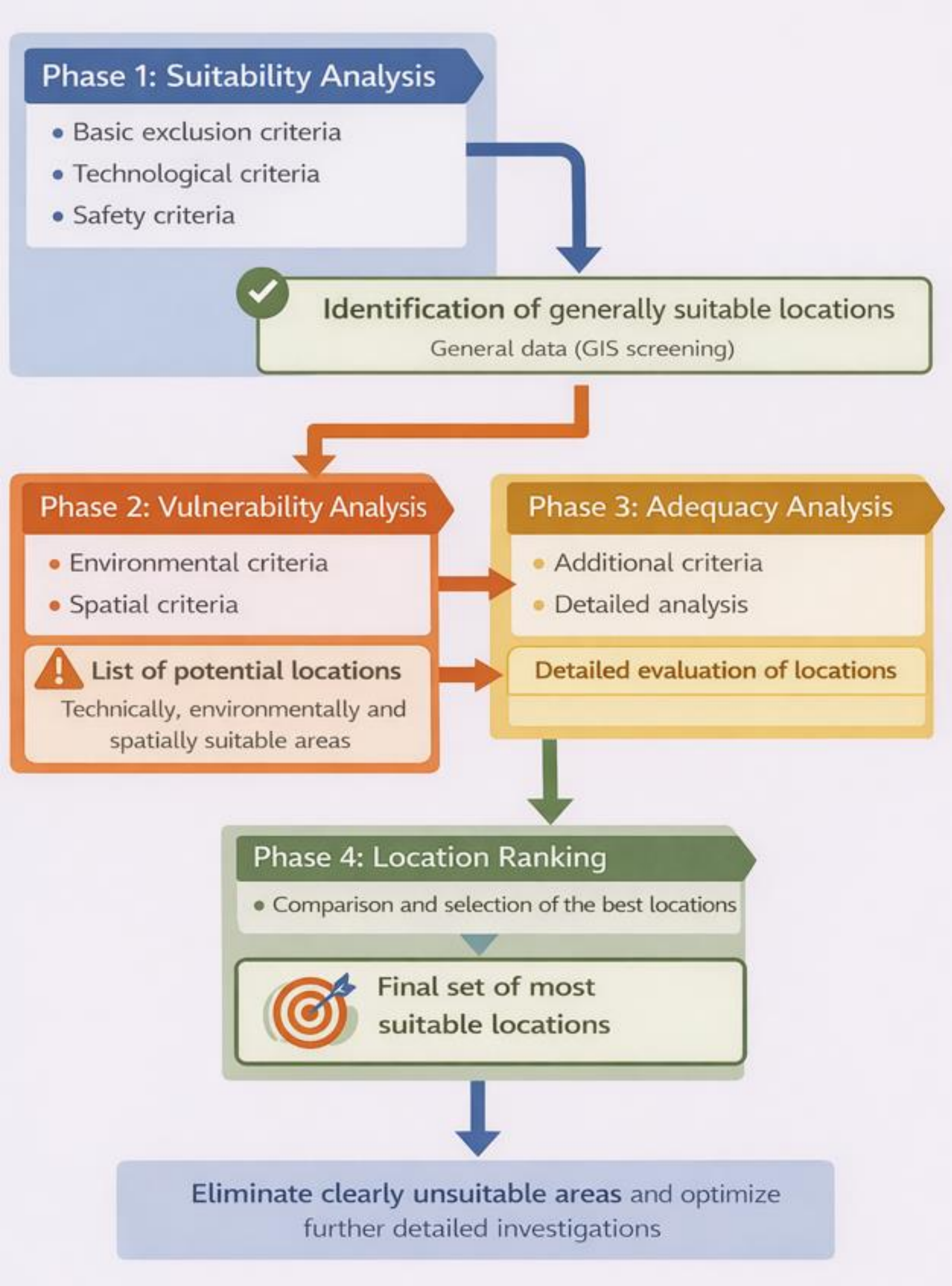

Figure 1: Scheme of the methodology used to search for locations for SMRs in Slovenia

3 SUITABILITY ANALYSIS – TECHNOLOGICAL SCREENING

The suitability analysis represents the first phase of the methodological procedure. In this phase, all areas that do not meet the basic technological conditions for the location of SMRs are systematically excluded from consideration, using exclusion criteria that define the technical feasibility of the project. This is a classic screening phase, in which individual criteria are considered as absolute conditions, and therefore areas that do not meet an individual criterion are excluded from further analysis, since the location of SMRs in such locations is not sensible or feasible from a technological perspective.

The most important technological exclusion criterion is the availability of cooling water. Although SMRs have significantly lower water needs than large nuclear power plants, a reliable water source is still a key condition for their operation. Watercourses with sufficient flow or the sea are considered as a minimum condition, and the maximum permissible distance of the location from a water source is additionally limited. This criterion in the Slovenian space significantly determines the spatial pattern of potentially suitable areas, as they are concentrated mainly along major rivers and on the sea coast.

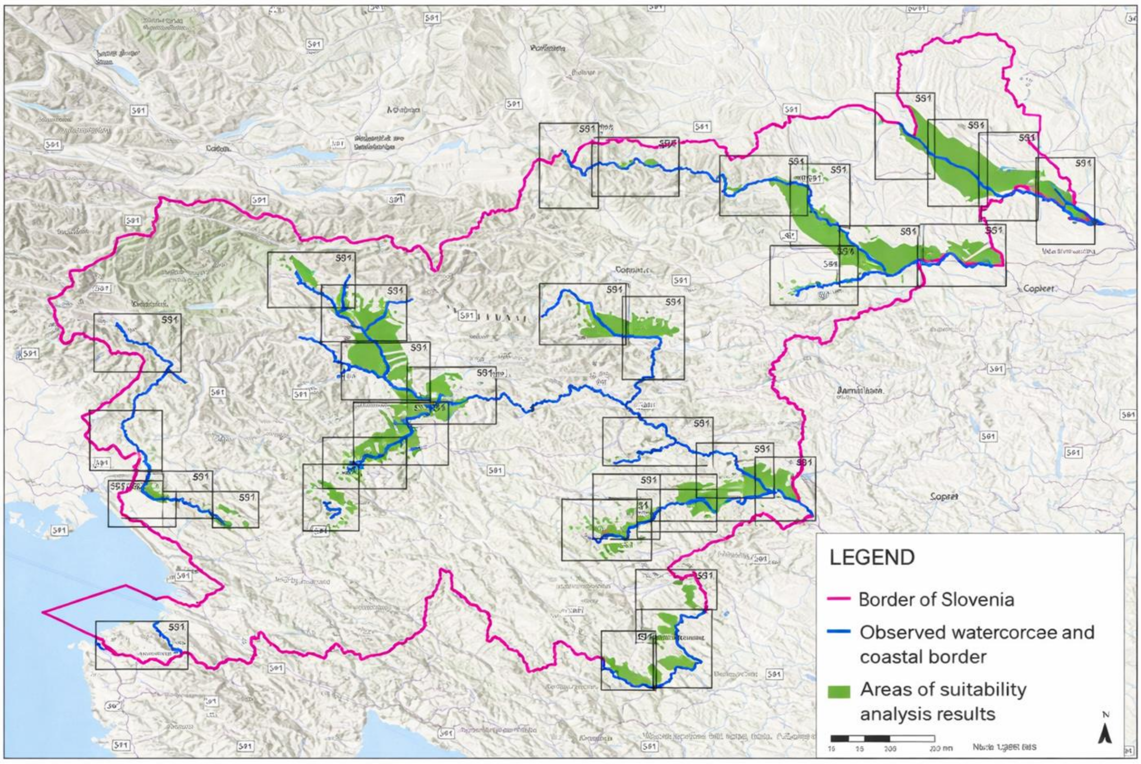

Figure 2: Result of suitability analysis

The second important set of technological exclusion criteria refers to the physical properties of the terrain. Nuclear facilities require flat and geomechanically stable terrain, therefore steeper areas, creeping and landslide terrains and areas with pronounced erosion processes are excluded from the consideration. In the Slovenian space, this criterion additionally limits the set of locations to flat and valley parts of the country. The third criterion is the availability of a sufficiently large and spatially appropriately designed area. The location of SMR requires a sufficient area for permanent occupation, accompanying facilities and a construction site, and at the same time the location must be functionally rounded and unfragmented. Narrow, fragmented or areas intersected by infrastructure corridors are not suitable because they complicate the technological organization of the space. Geological and seismic criteria are also particularly important. Areas in the immediate vicinity of geological faults (regardless of the type of fault) and areas with unfavorable geological conditions, including karst areas, where the presence of cavities, sinkholes and inhomogeneous substrates increases uncertainty regarding the foundations and stability of facilities, are excluded. It should be emphasized that this is an early engineering precaution. Regardless of the fact that detailed geological soil analyses are not available for most of the Slovenian territory to ensure the safety of nuclear facilities, from the perspective of early engineering precaution it is still sensible to exclude areas with greater geological uncertainty at an early stage **Error! Reference source not found.**.

The results of the suitability analysis show that technologically suitable areas in Slovenia are strongly linked to the valleys of major rivers. The highest concentration of potentially suitable areas occurs along the Drava, Sava and Mura rivers, partly also along other major watercourses and on the coast. In the northeast of the country, larger, compact areas of suitability are visible due to the flat relief and access to water. In contrast, the Alpine, Pre-Alpine and Karst parts of Slovenia are almost entirely excluded due to a combination of unfavorable relief, geological characteristics and limited availability of suitable water resources. The analysis thus shows that the availability of cooling water in combination with relief is the strongest limiting factor in the first phase of exclusion.

4 VULNERABILITY ANALYSIS – ENVIRONMENTAL AND SPATIAL FILTERING

Vulnerability analysis represents the second phase of the methodological procedure. In this phase, those areas where the siting of SMRs is not permissible from the perspective of environmental protection or legally defined spatial restrictions are further excluded from the set of technologically suitable areas.

While the first phase was focused on technical feasibility, the second phase focuses on environmental and spatial acceptability [10]. In this process, the protection criteria defined in the applicable national laws are used, which, due to the existing protection regimes, represent exclusionary restrictions. Areas where the intervention would be contrary to the guidelines of the applicable legislation or would cause unacceptable impacts on protected segments of the environment and spatial values are thus excluded from further consideration. Such protection restrictions include water protection areas where the siting of a nuclear facility would pose an unacceptable risk to drinking water sources, flood zones that pose a significant external threat to the facility, and nature areas, especially Natura 2000 and natural values, where the intervention could cause unacceptable impacts on habitats and species. Important environmental exclusion criteria are also cultural heritage sites, forest reserves and other protected areas where construction and operation would result in irreversible spatial change [16].

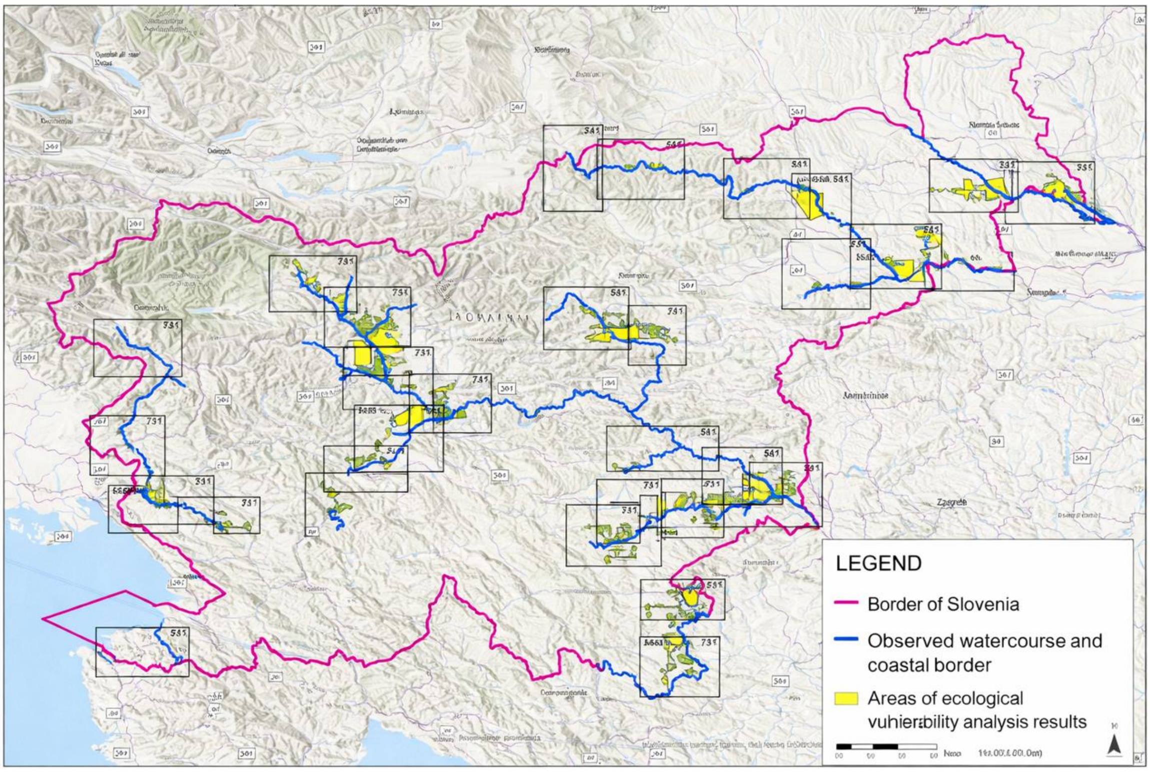

Figure 3: Result of environmental vulnerability analysis

In addition to environmental criteria, spatial and safety criteria are also considered in the vulnerability analysis phase. These include areas of exceptional landscapes where a larger energy facility would cause significant degradation of the landscape, and areas where the presence of airports, defense activities or industrial risks increases external safety burdens for a nuclear facility. This set of criteria stems from both spatial planning and general principles of nuclear safety, according to which the location of a nuclear facility should be removed from significant external sources of risk. The results of the vulnerability analysis confirm that the highest concentrations of vulnerable areas are directly linked to river corridors, especially along the Drava, Sava and Mura rivers.

The results were expected, as water protection areas, floodplains and Natura 2000 areas most often overlap along these watercourses. In the northeast of Slovenia, especially in Pomurje and Podravje, favorable technological conditions often overlap with high environmental sensitivity. In central Slovenia, there is also a pronounced overlap between suitability and vulnerability, which means that the area along major rivers is technologically interesting, but at the same time very limited in terms of protection regimes. Vulnerability analysis thus acts as a second, very important filter, significantly reducing the set of areas for further consideration.

5 ADEQUACY ANALYSIS – COMPARATIVE EVALUATION OF LOCATIONS

The third phase of the methodology is the suitability analysis. In this phase, the space is no longer narrowed by absolute exclusions, but locations are compared with each other on the basis of additional criteria. The suitability analysis considered 215 locations that had passed the previous exclusion phase. The suitability analysis focuses on constraints that are not of an exclusionary nature, but can significantly affect the implementation of the project. These criteria do not in themselves prevent placement, but they may represent additional technical, spatial, environmental or social challenges that need to be managed in subsequent phases with appropriate expert bases, technical solutions and mitigation measures. The purpose of the suitability analysis is therefore to identify the key challenges of an individual location and assess their manageability. These challenges will be addressed with further expert bases, with priority given to better-assessed locations.

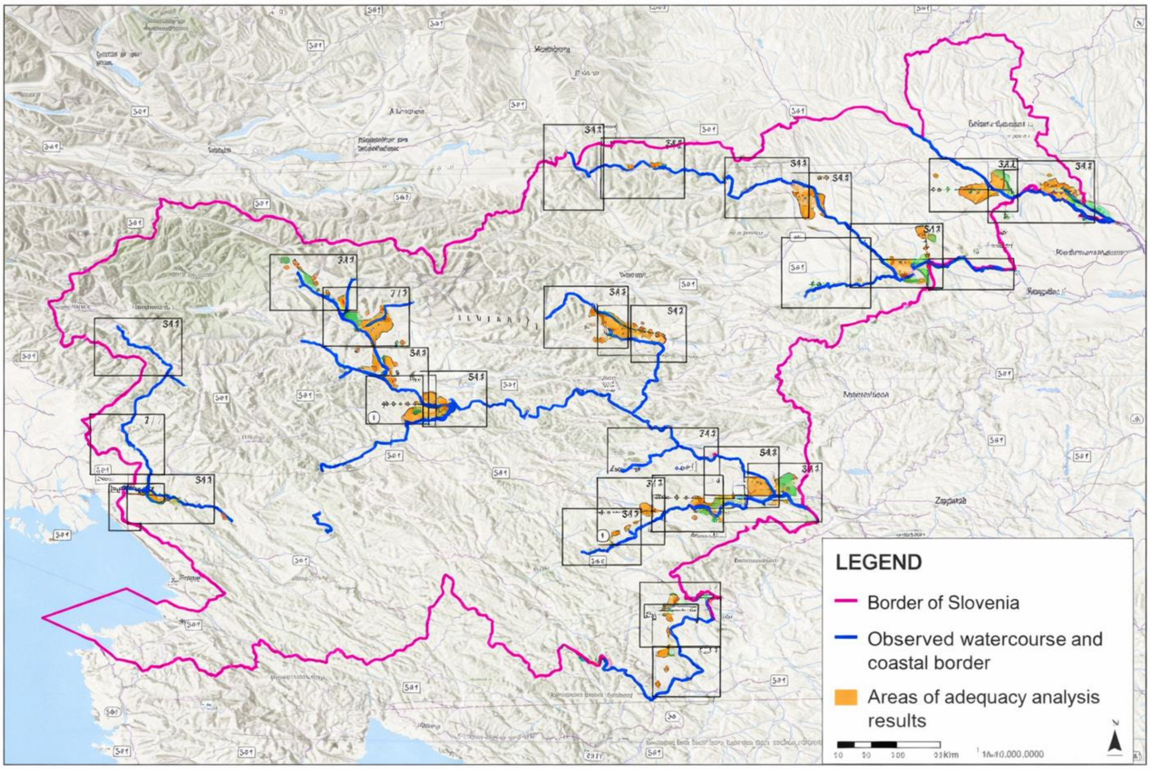

Figure 4: Overview of all 215 locations considered in the suitability analysis

6 LOCATION RANKING

The ranking represents the final phase of the methodological procedure. The ranking used criteria that are important from the perspective of technology, environmental protection, settlement and security risk for SMR. It is a further sifting of criteria that have already been discussed in terms of content in the suitability analysis, but were used in this phase in a way that allows for direct comparison of locations with each other. The purpose of the ranking is to determine the relative order of locations within the set of locations, according to the characteristics and complexity of solving the challenges of each individual location. This approach enabled an additional narrowing of the selection from the initial 215 considered locations to a manageable set of the best-rated locations, which it makes sense to process in more detail in later phases of project development. All criteria relevant for ranking locations are assessed according to a single four-level scale, where a score of 1 means the most favorable situation and a score of 4 the least favorable. The four-level scale was chosen to allow for sufficient differentiation between locations, while remaining transparent and methodologically robust. A three-level scale would be too rough in the case under consideration and could lead to too many equally rated locations, while a five- or more-level scale would require more precise data and introduce more subjectivity in determining the classes. A single scale allows for a direct comparison of different criteria and their combination into a common assessment without additional weighting. The ranking includes technological, environmental, spatial and safety criteria. Among the technological ones, the size of the location, proximity to a water source and the possibility of connecting to the electricity grid are important. Among the environmental ones, the complexity of the remaining protection regimes, which can still be managed with appropriate measures, is assessed. Spatial criteria include proximity to settlements, population density, proximity to major electricity consumers and the possibility of revitalizing degraded areas. Safety criteria mainly include the presence of risk factors in the surrounding area and proximity to geological faults. Based on the sum of individual assessments, locations are classified into classes. Locations with a lower number of points represent a more favorable combination of technological, spatial and environmental conditions and have fewer restrictions for further development. Such an approach enables transparent comparison of locations and determination of a priority set for further research. For the ten best-rated locations, a SWOT analysis is also prepared in the final phase, which identifies their strengths, weaknesses, opportunities and threats. In addition, a set of further activities is determined for each of these locations, which must be carried out in the event of a decision on further development of the location. These activities include the preparation of more detailed geological, geomechanical, seismological, hydrological and environmental bases and verification of infrastructure, spatial conditions and the possibility of involving stakeholders

7 CONCLUSION

The presented methodology is designed as an early, multi-stage and data-supported spatial analysis, the purpose of which is not to finalize the location of SMRs, but to identify areas where it makes sense to further consider the location of such facilities in Slovenia. Its essential value lies in the fact that it combines technological, environmental, spatial and safety aspects in a transparent, repeatable and methodologically consistent manner and enables the initial classification of locations according to their development prospects. At the same time, the methodology also clearly shows the limitations of Slovenian space. The most favorable technological conditions often occur in areas that are most sensitive from an environmental and spatial perspective. In addition, due to the limited availability of data in the field of nuclear safety, only an initial spatial analysis can be carried out, but not a final assessment of suitability. This means that the results do not represent a final decision, but rather the basis for further, significantly more detailed planning phases. This is precisely the key importance of the methodology. It enables rational targeting of further research to those locations where, based on currently available data, the least limitations can be expected, or challenges that

can be managed with engineering solutions, additional expert bases and measures to reduce impacts.
The methodology thus represents a robust framework for the initial identification of potential SMR locations in Slovenia and an expert starting point for further strategic decision-making on the development of nuclear energy in Slovenia.

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