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Multi-Criteria Studies and Assessment Supporting the Selection of Locations and Technologies Used in CO_2-EGS Systems

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Citation: Pająk, L.; Sowiżdżał, A.; Gładysz, P.; Tomaszewska, B.; Miecznik, M.; Andresen, T.; Frengstad, B.S.; Chmielowska, A. Multi-Criteria Studies and Assessment Supporting the Selection of Locations and Technologies Used in CO_2-EGS Systems. *Energies* **2021**, *14*, 7683. https://doi.org/10.3390/en14227683

Academic Editor: Gianpiero Colangelo

Received: 8 October 2021
Accepted: 11 November 2021
Published: 17 November 2021

Abstract: The paper describes application of the cross-impact method in the process of selecting locations and technologies used in a geothermal system based on energy accumulated in a dry rock formation, where CO_2 is used as the working medium. The survey is based on the opinion of a group of 20 experts representing different fields of earth and technical sciences. They represent Norway and Poland, where the location of such a system is considered. Based on experts' experience and opinions, all factors that seem to be significant were classified into the following groups: targets, key factors, results, determiners, motor and brakes, regulating factors, external factors, auxiliary factors, and autonomous factors. Direct influences between variables were indicated. Due to major differences in geological conditions in Poland and Norway, the factor of on- or offshore technology was pointed out as the primary determiner. Among key factors, the system operation's long-term safety and level of technological readiness were indicated. As a target factor, an interest of local authority was pointed out. Among the variables that are important when selecting locations for this type of system, nine are essential: (1) Formal constraints related to local nature protection areas—this variable is essential in the case of an onshore system; (2) Availability of CO_2 sources; (3) Level of geological recognition; (4) The distance of the CO_2-EGS from a thermal energy user and electricity grid; (5) Existing wells and other infrastructure; (6) Depth of the EGS system; (7) Water depth if offshore, this variable is only important when offshore systems are involved; (8) Physical parameters of reservoir rocks; (9) Reservoir temperature.

Keywords: geothermal; Hot Dry Rock (HDR); Enhanced Geothermal System (EGS); CO_2 sequestration; cross-impact method; MICMAC

1. Introduction

Geothermal energy is being utilised worldwide using different technological solutions, depending on resource temperature and the accessibility of a medium from which it is possible to obtain energy. Among all clean renewables, geothermal stands out due to its stability and the accessibility of energy independent of weather conditions. Stable access to an energy source is guaranteed when the size of a geothermal reservoir, by which is meant its volume, is significant. The standard method of obtaining geothermal energy is linked to the combination of potentially high temperatures and the availability of a fluid, which is usually water or brine. This fluid is a carrier that enables the acquisition and extraction of the geothermal energy which is brought to the earth's surface. Frequent consideration is given to a method of obtaining geothermal energy independent of access to a fluid, allowing geothermal energy to be extracted using a heat carrier injected from the surface, which receives heat from geological formations and carries it to the surface. This technology used to be called Hot Dry Rock (HDR) but nowadays the name Enhanced Geothermal Systems (EGS) is commonly used [1], for rocks that are not completely dry, but the amount of water contained in them does not allow to sustain stable energy production. The operating principles of both of these systems are similar, which is the idea of extracting energy contained in a dry or closed reservoir by creating an artificial reservoir with enhanced permeability through which a working fluid can flow. Sometimes, some fluid already exists inside fractures or pores, but often the rock matrix is dry and has to be artificially fractured to create a permeable zone. The first case refers to EGS, while the second to HDR. Such systems are already operating in the world, and the first long-term effects of their exploitation show potential for further development of these technologies [2]. There are several model studies and plans for introducing these technologies in real conditions and theoretical work related to the possibility of using this technology has also been carried out in Poland [3–7]. Water is almost always used as a heat transfer medium in such installations. However, more fluids could be as effective or even surpass water, e.g., considered here CO_2. It could turn out that for energy extraction its physical properties are even better than those of water. For example, CO_2 is generally less viscous, which could result in smaller flow resistance between wells forming the geothermal doublet. Therefore, a system utilising supercritical CO_2 as the working fluid, including partial CO_2 sequestration is considered in this article. Preliminary research on the use of CO_2 as a heat transfer fluid in enhanced geothermal systems are numerous—some of them are following [8–12]. Tarkowski et al. [13] also analysed the legal conditions for injection of CO_2 and geothermal energy recovery. From the literature study, the projected effects of the system's operation seem to be promising. Additionally, it can be expected that partial sequestration of CO_2, which improves the ecological effect of the system, will contribute to gradual decarbonisation. In the work of Cui et al. [14] interesting results are described. The work is based on numerical simulations where it was indicated that due to higher mobility of CO_2 compared to water at a low permeable reservoir, CO_2 might be a more suitable working fluid than water, as CO_2 allows reaching higher net power of a geothermal system. In turn, according to Avanthi Isaka et al. [15], supercritical CO_2 has favourable characteristics in terms of reservoir stimulation due to the creation of complex fracture networks.

The total cost of energy obtained based on a high-temperature depleted gas reservoir by recycling CO_2 is estimated by Cui et al. in [16]. Depending on a surface installation scheme, the cost is estimated at 0.1 USD/kWh when a turbine is driven directly by CO_2 and 0.45 USD/kWh when the Organic Rankine Cycle is used. Direct use of CO_2 as working fluid allows reaching much higher power. The idea of the study described in [16] is a bit like the suggested case, but not the same. The concept of a reservoir is different, but the technology of energy production is similar.

The technical risk assessment associated with its implementation is extremely important at the stage of technological development. It is essential to locate the first pilot installations in optimal zones, encouraging future researchers and investors to develop the technology. The problem of identifying factors important for the support and further development of the technology being investigated is discussed in this article. The overriding goal was to identify factors relevant to the selection of the location of the CO_2-EGS system and to identify the interconnections between them. The study was carried out using the cross-impact method based on the opinion of a group of 20 experts representing a multidisciplinary team.

This work is the first part of the EnerGizerS project carried out by the Polish-Norwegian scientific team. The main goal of the project is to analyse the efficiency of EGS using CO_2 as a working fluid. The proposed solution is intended to take action to protect the climate by producing clean and ecological geothermal energy while simultaneously reducing carbon dioxide emissions coming from the combustion of fossil fuels.

2. Method Description

Structural analysis is a method that helps to structure ideas on this subject. It provides the possibility of describing a system by a matrix connecting relations between chosen components. By studying these relations, the method provides the opportunity to reveal the variables essential to the system's evolution. It is possible to use the technique alone (as a help for reflection and/or decision making) or as a more complex activity (scenarios). The decisional structural analysis used as a tool of representation of players' games is very well presented in the book of Tenière-Buchot [17]. Godet [18] created the MICMAC Forecasting method and software suitable for analysing it. Based on the qualitative independent judgment of a group of experts, the method allows one to define the influences of the appointed variables and their dependence on the other variables. The group of experts should be as multidisciplinary as possible, however, its competencies should coincide widely with the topic of a study. The final results place all appointed by the group of experts and assumed to be crucial parameters in the space of influence-dependence (Figure 1). The horizontal axis is the axis of dependencies and the vertical axis is the axis of influences. The most important is the possibility of defining those variables that strongly influence others or depend strongly on others. If the influence value is high, it means that by changing those variables, we can improve or worsen key factors. Especially important is a strong influence on the variables strongly dependent on others. Otherwise, it can be said that factors characterised by the low influence and low dependence are not important, but the possibilities of indicating them might be crucial due to further activities. The groups of factors set on the surface of influence-dependence (Figure 1) possess their typical features:

- Key factors—indicating which actions should be given priority in the development of strategic plans,
- Targets—the evolution of these factors will depend on how other system variables evolve. They involve variables that change themselves to a large extent under the influence of factors other than those that affect them directly,
- Results—the evolution of these factors will depend on how other system variables evolve. They have a low impact on the structure of the research area but are very dependent on other factors,
- Determiners, motors and brakes—have a powerful impact on the system so that they can act as drivers and inhibitors, but they are tough to control. Knowledge of these is essential in the process of observing long-term trends in the study of the future,
- Regulating factors—can help achieve the strategic objectives. Do not have any strong dependencies on other factors. Their effect on the whole system is not decisive,
- External factors—significantly influence the process being considered but cannot be controlled,
- Auxiliary factors—can help to achieve the strategic objectives, but their effect on the whole system is not decisive,
- Autonomous factors—have a negligible impact on the changes taking place in the system as a whole.

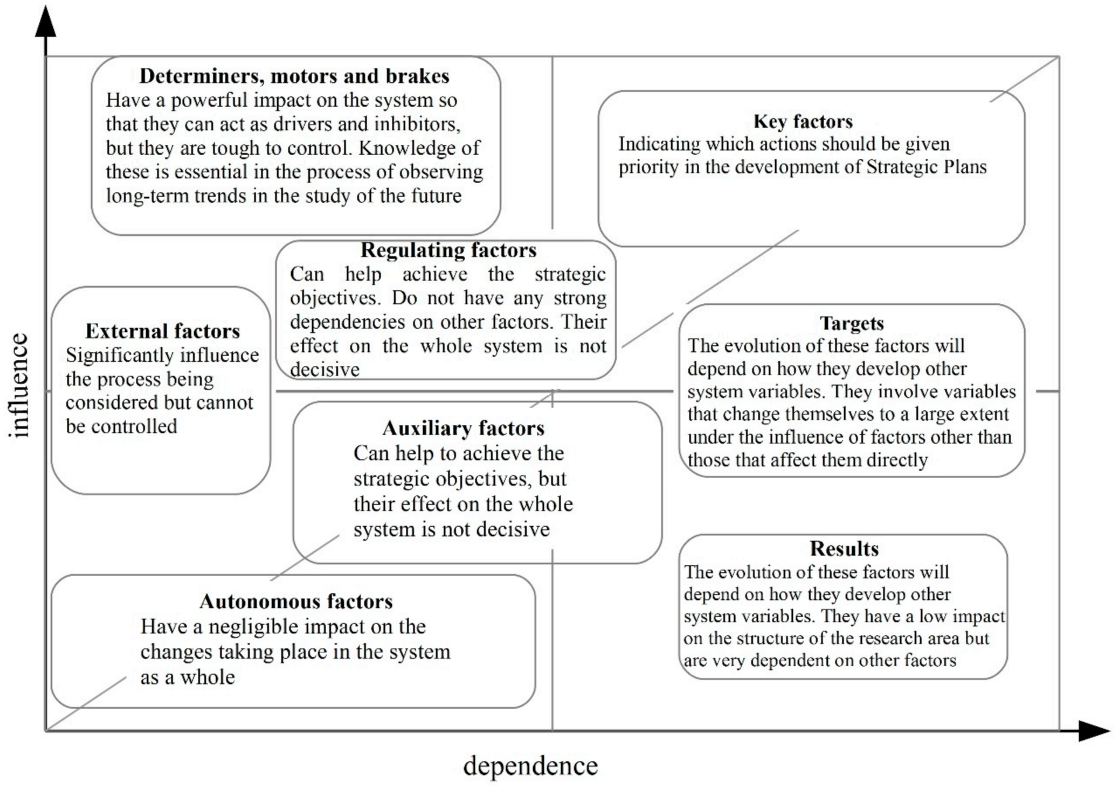

Figure 1. Definition of the location of important factors in the dependence-influence surface, based on the method description.

One of the widely available free software which is helpful during data processing is MICMAC, a computer program that was used to prepare this paper. The latest available version of the MICMAC is version 6.1.2, 2003/2004, open-source software license [19]. The software was developed and is delivered by LIPSOR—the Laboratory for Investigation in Prospective Strategy and Organisation. The name of the method, MICMAC, refers to the French acronym for Cross-Impact Matrix Multiplication Applied to Classification. The software was used to analyse data related to various fields, from architecture [20] to the issues associated with forecasting technological development and forecasting in general [18,21].

3. Survey Description

The survey was carried out in 9 steps described briefly in Figure 2. It started with problem definition and a description of the goals of the survey. The primary target is to point out the most important variables of the CO_2-EGS system and find a relationship between them. Special emphasis is put on variables that are important for system location. The survey was held based on the experience of a group of experts. A group of 20 experts was chosen. The experts were drawn from the two nations that were subjects of the survey, that is Poland and Norway, the group containing 12 Polish experts and 8 Norwegian experts. The fields of experience of the experts were different, and each expert was able to indicate more than one field of experience. In the end the group of experts contained 7 experts on geology, 4 experts in the field of reservoir engineering, 12 experts on environmental impact assessment, one expert on the legal aspects related to mining matters and requirements, 5 experts on economic matters, and 2 experts on risk assessment. At the preliminary survey stage, the role of each expert was to rethink the problem and goals described and indicate at least 10 variables that influenced them. Depending on the stage of the surveys, 193 important variables were defined and some of the repetitions were removed. The list of variables was analysed to remove logical repetitions, combine independent variables by creating new ones, and remove variables obviously falling out of the scope of the survey.

The target in that case was to reduce the number of assumed variables keeping sense of the main ideas. After that stage of the survey, all the experts could express their opinion on whether they approved of the new reduced list of variables or not. They could also add new variables if it was felt necessary. Based on the opinion of the Norwegian experts, the list of variables was extended by 2 variables related to offshore technology, very important in the case of Norway but almost unimportant in Poland. Finally, the list of variables that seem to be important included 48 variables. The variables were combined in the range of interdisciplinary thematic groups: geological (containing 13 variables), legal and policy (5 variables), economy (9 variables), technical (11 variables), transportation and logistics (3 variables), environment (4 variables), and social (3 variables). The list of variables indicated and finally selected by the experts is attached in Table 1. Appendix A extends the description of variables and provide additional explanations. Based on the list of variables indicated and considered as important, a matrix of influences (MOI) was constructed (Figure 3). MOI contains the list of variables in the first column and the list of the same variables in the first row. The task of each expert was to estimate how each variable in the row influences variables in columns. An expert judged the influence of one variable on another by choosing a weight of influence in the range of 0–3, where values 0 means no influence, 1—weak influence, 2—moderate influence, and 3—strong influence. The method used in the MICMAC software allows one to set a value of influence as potential influence “P”. In the work presented, it was assumed that experts would only use quantitative values of influences, excluding “P”. It is worth emphasising that the adopted method of filling the matrix causes it to not be symmetrical in relation to the diagonal. For example, variable no 39 (The degree of urbanisation of the area—Table 1) strongly influences variable no 3 (Quality of air—Table 1), so the value of the influence weight was determined to be 3 (Figure 3). On the other hand, the impact of variable 3 on variable 39 was assessed as weak, equal to 1 (Figure 3). The diagonal is filled by 0, but in fact is disregarded by the program. The MOI was filled by all the experts individually in as short a period of time as possible. After that, all the data were combined, and the final MOI was presented. Values were assigned by calculating arithmetic mean values, rounded to the nearest integer.

Further data processing was completed by the MICMAC software using all the default settings suggested by the software. Based on the results, further evaluations were held as described.

The variables in Table 1 are marked by colour, depending on their classification to the thematic scope. The same colour scheme is used in Figures 3 and 4, where variables ID number is placed in the first row and column.

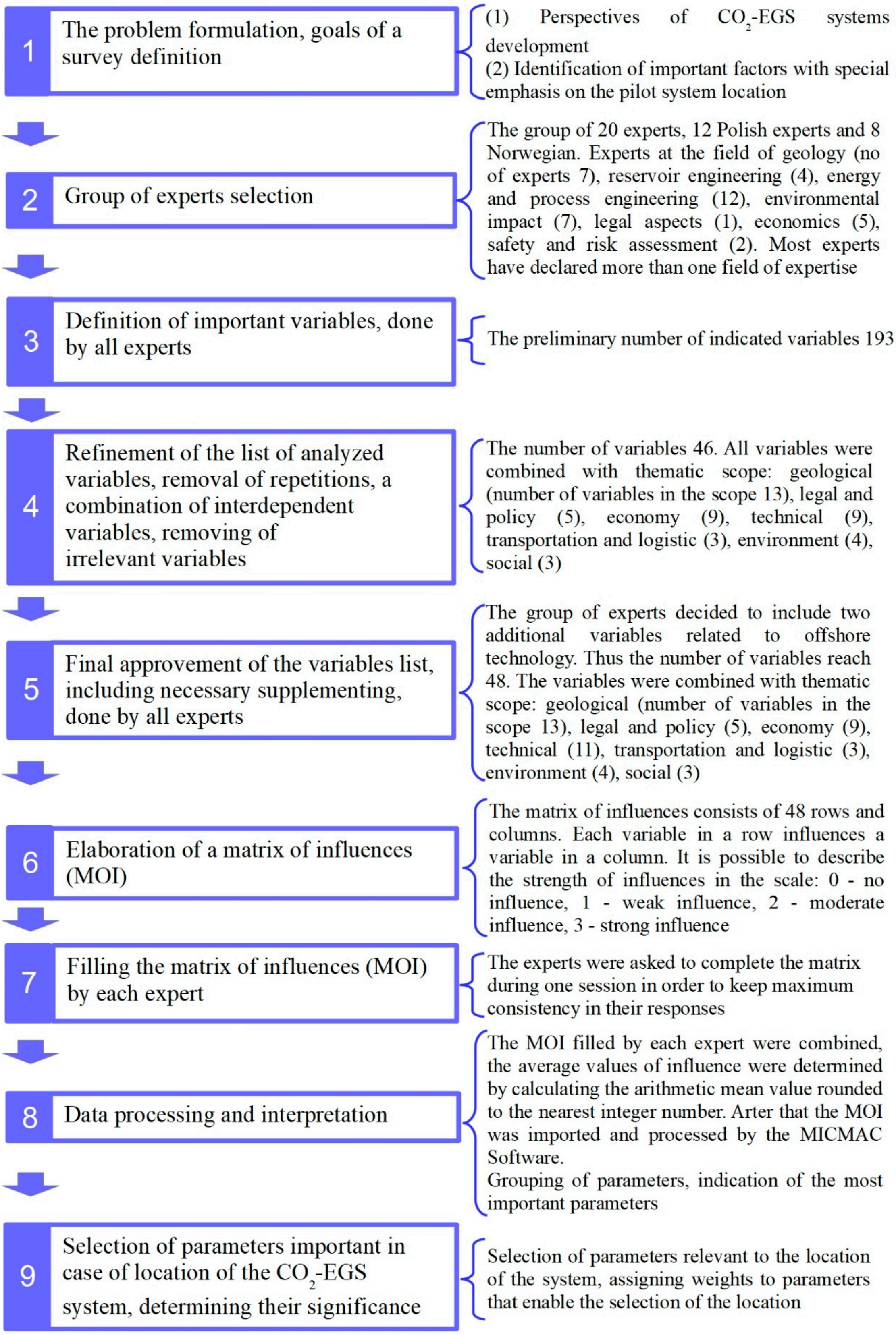

Figure 2. Description of the stages of the survey.

Table 1. List of important variables indicated by the expert group for CO_2-EGS technology.

No	Long Label	Short Label	Thematic Scope
1	Formal constraints related to a local nature protection area	RestrictEnvLoc	Environment
2	Current primary energy carrier for heat supply	UsedHeatSource	Environment
3	Quality of air	AirQuality	Environment
4	Long term safety when exploiting the CO_2-EGS system	LongThermSafety	Environment
5	Power and energy demand of direct energy user (DHS) [1]	UserP&Q	Technical
6	Supply temperature requirements of direct energy user (DHS)	UserTemp	Technical
7	Availability of CO_2 sources	AvailResCO$_2$	Technical
8	Availability of cooling water (ground, river, lake, sea)	AvailCoolWater	Technical
9	Level of Technological Readiness	TechReaLev	Technical
10	CO_2-EGS system operational parameters	CO$_2$EGSoperPrm	Technical
11	Availability and stability of time-dependent parameters	TimeDesignPrm	Technical
12	Equipment and machinery for supercritical utilisation of CO_2	EandMsCO$_2$	Technical
13	Existing wells and other infrastructure	ExistWells	Technical
14	Onshore/offshore	OnOffShore	Technical
15	Water depth if offshore	WaterDepthOff	Technical
16	Cost of obtaining CO_2 at a specific location	CO$_2$Cost	Economy
17	Geothermal system risk insurance fund	GeoRiskInsurance	Economy
18	Financial support for CO_2-EGS systems in an early stage of technological development	FinSuppCO$_2$EGS	Economy
19	Accuracy of CAPEX estimate—especially for drilling and fracturing	AccurInestDrillFrac	Economy
20	CO_2 emission price	CO$_2$emPrice	Economy
21	Preferable tax discounts	TaxDisc	Economy
22	Cost of drilling and fracturing	DrilingFractCost	Economy
23	Price of heat and electricity on the energy market	EnergyActualPrice	Economy
24	Cost of energy obtained by the CO_2-EGS system	CostOfEnCO$_2$EGS	Economy
25	Hydrogeochemical information	HydroGeochem	Geology
26	Availability of other underground resources	AvailOtherResour	Geology
27	Geological recognition level	GeolRecog	Geology
28	Physical parameters of reservoir rocks	RocksPhysicPrm	Geology
29	Presence and distribution of natural faults and fractures	FractPres&Distr	Geology
30	Potential for hydraulic stimulation (fracturing) of the geological formation	PotentFract	Geology
31	Natural seismicity at the EGS site	Seismicity	Geology
32	Stratigraphy and lithology, geological structure	Strat&Lithology	Geology
33	Reservoir temperature	TempResources	Geology
34	Hydrogeological conditions	HydrogolCondition	Geology
35	Depth of the EGS system	DepthEGS	Geology
36	Thickness and tightness of isolating overburden	CapRock	Geology
37	Thickness of reservoir	ThicknessRes	Geology
38	The distance of the CO_2 EGS from a thermal energy user and electricity grid	DistanceGrid	Transportation and logistics
39	The degree of urbanisation of the area	UrbanArea	Transportation and logistics
40	Access to surface infrastructure	AccessSurfaceInf	Transportation and logistics
41	Qualified personnel for the development and operation of CO_2-EGS	ManPower	Social
42	Social acceptance of CO_2-EGS	SocialAcceptEGS	Social
43	Good practice and examples of utilisation of geothermal energy	GoodPractGeoHeat	Social
44	Energy security and policy	EnergySecurity	Legal and policy
45	Local authority interest	AuthInterest	Legal and policy
46	Local regulations on the utilisation of geothermal energy	LocalRegulatGeo	Legal and policy
47	Local regulations on CO_2 storage	LocalRegCO$_2$stor	Legal and policy
48	Land ownership type	LandProperty	Legal and policy

[1] DHS—District Heating System.

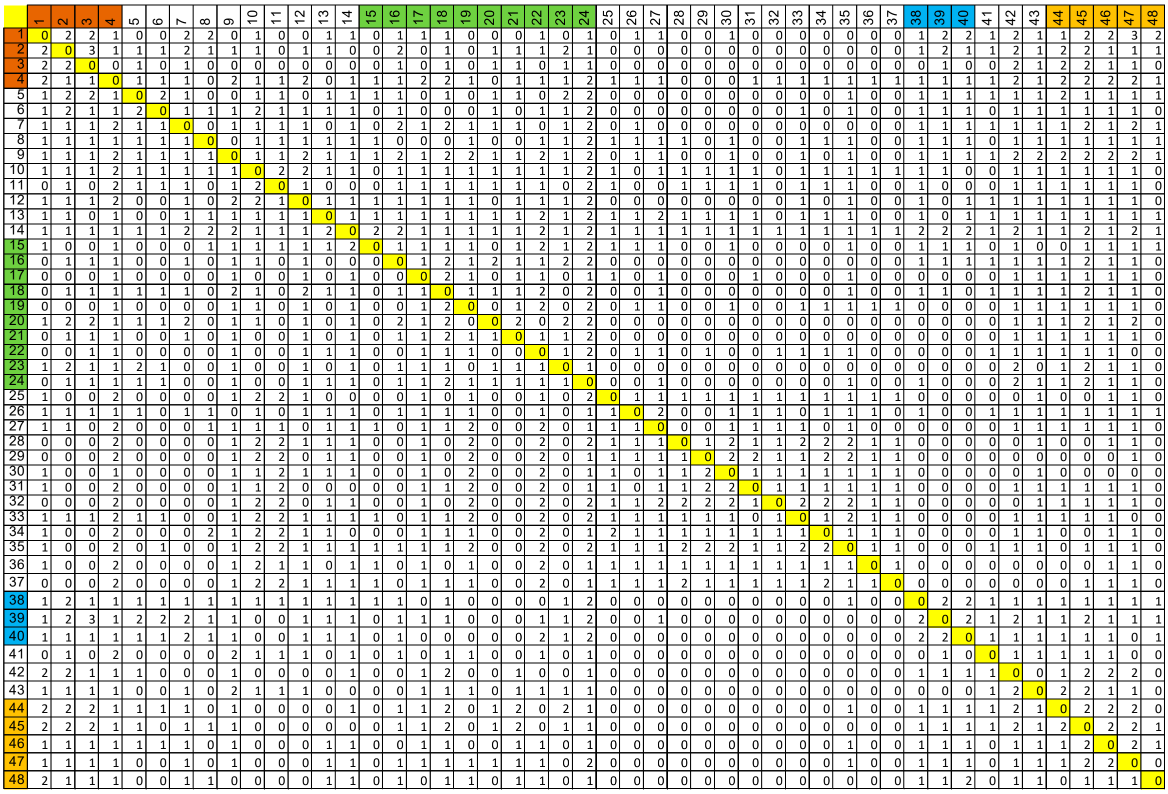

Figure 3. The average values of influences (numbers of rows and columns—the coloured areas correspond to the description of the variable; see Table 1).

Figure 4. Values of standard deviations (numbers of rows and columns and the coloured areas relate to variables corresponding to the description of the variables—see Table 1).

4. Results

Figure 3 shows the final structure of the final matrix of influences (MOI). The numbers describing the impact of the factors are mean values. Figure 4 shows values of the standard deviations for each cell of the MOI. The values of the standard deviations indicate the differences between the answers entered by the experts. The values of the standard deviation cover the range from 0 to 1.4. It may be noted that the lowest values of standard deviation in the case of a variable influence can be seen with “Social acceptance for CO_2-EGS”. The standard deviations of influences have the highest values with the variable “Onshore/offshore”. The experts’ opinions in the case of this variable are described with the greatest uncertainty. In the case of dependences, the lowest value of standard deviation is related to the “CO_2 emission price” and the highest to “Local authority interest”.

Figure 5 shows the diagram of direct influences. The location of variables was determined as a result of data processing by the MICMAC software. Additionally, the original graph was supplemented on the ranges of parameters groups located at typical places on the dependence-influence surface (Figure 1). The range of the “External factors” and “Targets” groups in Figure 5 are slightly extended in the lower values of influence when compared to Figure 1. The “Results” group is extended to higher values of dependence. The extended ranges are marked with a green dashed line. Extending the scope of the data can be considered as a preliminary interpretation of the data. Variables that were originally outside the ranges typical for each group were included in specific groups on the basis of the authors’ judgement. However, it should be remembered that the method determines the position of the variable groups (Figure 1) in an approximate manner.

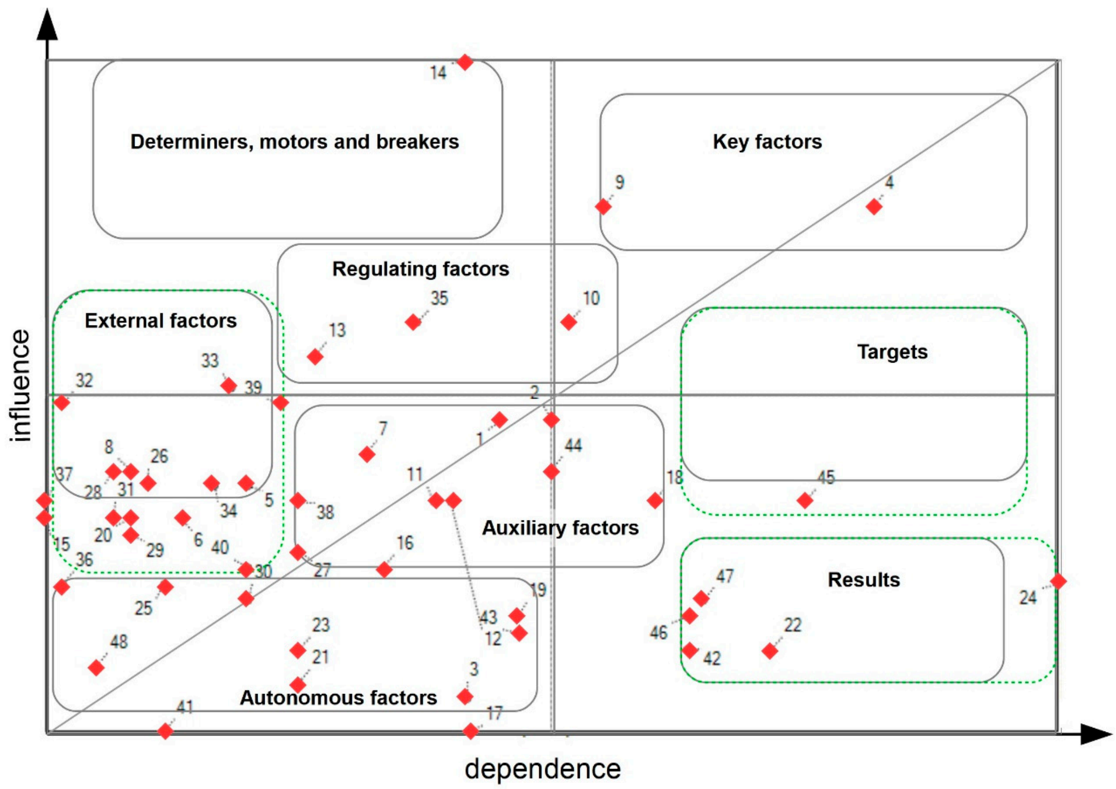

Figure 5. Diagram of direct influences, the numbers in the graph correspond to the variables’ numbers in Table 1.

The direct influences graph is presented in Figure 6. A relatively strong influence can be observed with the variables indicated (e.g., “A → B” one sided influence, variable A influences variable B, “A ↔ B” both sides influence each other, A influences B, but B influences A). It can be noted that a strong direct influence is noticeable with three pairs of variables:

- variables 1 → 47, the "Formal constraints related to a local nature protection area" strongly influence the "Local regulations on CO_2 storage", the weight of influence is estimated as 3 (where 0 means no influence and 3 is the strongest influence),
- variables 2 → 3, the "Current primary energy carrier for heat supply" strongly influences the "Quality of air", the weight of influence is 3,
- variables 39 → 3, the "The degree of urbanisation of the area" strongly influences the "Quality of air", the weight of influence is 3.

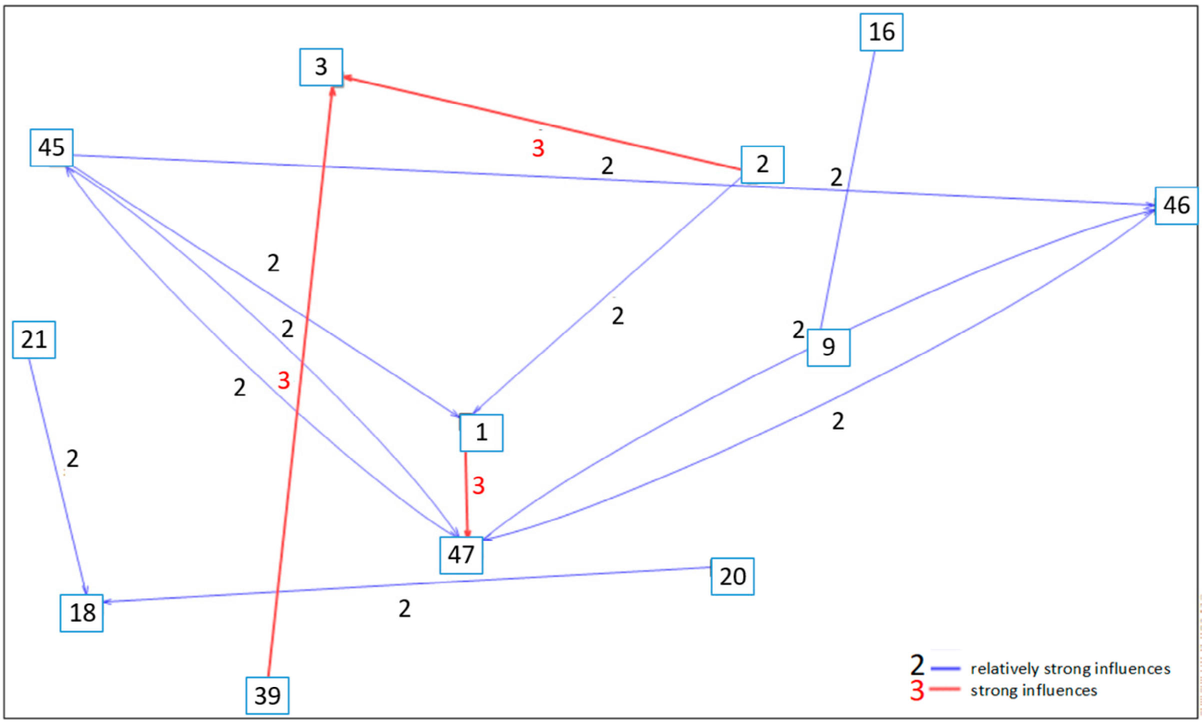

Figure 6. Direct influences graph, the numbers in the graph correspond to the number of the variables in Table 1, the result of data processing by the MICMAC software.

The result of strong influences (the weight of influence is 2) is related to:

- 21 ("Preferential tax discounts") → 18 ("Financial support for CO_2-EGS systems in an early stage of technological development"), the influence is obvious,
- 20 ("CO_2 emission price") → 18 ("Financial support for CO_2-EGS systems in an early stage of technological development"), the price of CO_2 emissions might affect the financial support for the CO_2-EGS. However, the price of the emissions might support solutions able to reduce it. Variable 20 belongs to the group of "External factors" (Figure 5),
- 47 ("Local regulations on CO_2 storage") ↔ 45 ("Local authority interest"), the influence is quite obvious,
- 45 ("Local authority interest") → 1 ("Formal constraints related to a local nature protection area"), the influence of "Local authority interest" affects the "Formal constraints",
- 45 ("Local authority interest") → 46 ("Local regulations on the utilisation of geothermal energy"), from this result it obviously appears that the local interest influences local regulations,
- 2 ("Current primary energy carrier for heat supply") → 1 ("Formal constraints related to a local nature protection area"), one can find logical connections between the variables. It is preferable that the areas where the use of fuels that pollute the environment by combustion products is allowed were not nature protection zones. Establishment of a protection zone suggests the use of clean energy sources,

- 47 ("Local regulations on CO_2 storage") ↔ 46 ("Local regulations on geothermal energy utilisation"), the interrelation between variables seems to be reasonable,
- 9 ("Level of Technological Readiness") → 16 ("Cost of obtaining CO_2 at a specific location"), the influence of these variables seems to be illogical.

Based on the results presented in Figure 5, groups of factors can be seen (the number corresponding to the number of factors—see Table 1), the groups of factors being described in Table 2. The priority actions that need to be completed if the CO_2-EGS technology is going to be used are at the level of long term safety and technological readiness. These are clearly described as "Key factors". Local authority interest ("Targets" group) depends on many factors that not only influence it directly. Among all the variables belonging to the Results group, the "Cost of energy obtained by the CO_2-EGS system" is primarily dependent on other variables. The primary technology division into on- and offshore (the variable "OnOffShore", no. 14 in Table 1) has a substantial impact on the system. The choice depends on the system location, and it is out of the investigator's control. Thus, its allocation to the group of "Determiners, motors and breakers" looks logical. The composition of the group of "External factors" describes current situations. With time, the parameter described by some variables can change. However, in the case of checking this in its current state, all variables look to be in the proper place on the influence-dependence surface (Figure 5). A similar situation can be observed in cases of "Auxiliary" and "Autonomous factors".

Table 2. Assignment of variables to parameter group factors.

Variable Number (see Tables 1 and A1)	**Brief Description of the Variable**
Key factors (indicating which actions should be given priority in the development of Strategic Plans)	
4	Long term safety when exploiting the CO_2-EGS system
9	Level of Technological Readiness
Targets (the evolution of these factors will depend on how they develop other system variables. They involve variables that change themselves to a large extent under the influence of factors other than those that affect them directly)	
45	Local authority interest
Results (the evolution of these factors will depend on how they develop other system variables. They have a low impact on the structure of the research area but are very dependent on other factors)	
22	Cost of drilling and fracturing
24	Cost of energy obtained by the CO_2-EGS system
42	Social acceptance of CO_2-EGS
46	Local regulations on the utilisation of geothermal energy
47	Local regulations on CO_2 storage
Determiners, motors and brakes (have a powerful impact on the system so that they can act as drivers and inhibitors, but they are tough to control. Knowledge of these is essential in the process of observing long-term trends in the study of the future)	
14	Onshore/offshore
External factors (significantly influence the process being considered but cannot be controlled)	
10	CO_2-EGS system operational parameters
13	Existing wells and other infrastructure
35	Depth of the EGS system
5	Power and energy demand of direct energy user (DHS)
6	Supply temperature requirements of direct energy user (DHS)
8	Availability of cooling water (ground, river, lake, sea)

Table 2. *Cont.*

Variable Number (see Tables 1 and A1)	Brief Description of the Variable
15	Water depth if offshore
20	CO_2 emission price
26	Availability of other underground resources
28	Physical parameters of reservoir rocks
29	Presence and distribution of natural faults and fractures
31	Natural seismicity at the EGS site
32	Stratigraphy and lithology, geological structure
33	Reservoir temperature
34	Hydrogeological condition
37	Thickness of reservoir
39	The degree of urbanisation of the area
40	Access to surface infrastructure
Auxiliary factors (can help to achieve the strategic objectives, but their effect on the whole system is not decisive)	
1	Formal constraints related to a local nature protection area
2	Current primary energy carrier for heat supply
7	Availability of the CO_2 sources
11	Availability and stability of time-dependent parameters
16	Cost of obtaining CO_2 at a specific location
18	Financial support for CO_2-EGS systems in an early stage of technological development
27	Geological recognition level
38	The distance of the CO_2-EGS from a thermal energy user and electricity grid
43	Good practice and examples of utilisation of geothermal energy
44	Energy security and policy
Autonomous factors (have a negligible impact on the changes taking place in the system as a whole)	
3	Quality of air
12	Equipment and machinery for supercritical utilisation of CO_2
17	Geothermal system risk insurance fund
19	Accuracy of CAPEX estimate—especially for drilling and fracturing
21	Preferable tax discounts
23	Price of heat and electricity on the energy market
25	Hydrogeochemical information
30	Potential for hydraulic stimulation (fracturing) of the geological formation
36	Thickness and tightness of isolating overburden
41	Qualified personnel for the development and operation of CO_2-EGS
48	Land ownership type (private ownership, local government ownership)

5. Critical Recommendation for the Selection of Parameters Used for the Location of Potential Zones for CO_2-EGS

The selection of an appropriate location for the construction of a CO_2-EGS system is extremely difficult, especially in places where such systems do not exist yet, and the selected location has a chance to become a pilot location. A number of factors may determine the success of such an investment. In addition to the obvious geological factors, other factors such as legal and environmental must also be taken into account. These factors may limit the choice of location in areas that might geologically seem suitable. System CO_2-EGS is a system where CO_2 is used as the working medium. Therefore, availability of CO_2 also influences the site selection. The MICMAC Forecasting method is particularly important when several locations have been initially identified. This method allows to select the most important parameters, categorise preselected locations, and choose the best one.

The geological areas under consideration (Norway and Poland) differ a lot in terms of geology and energy infrastructure. These differences affect the choice of location for the CO_2-EGS systems. In the case of Poland, the main sources of CO_2 and identified geological conditions are combined within onshore solutions. In the case of Norway, it is recognised that the geological conditions and CO_2 sources are located offshore or on the coast. The importance of this crucial difference is confirmed by the analyses completed for the diagram of the direct influences graph (Figure 5). The fundamental technological differences between offshore and onshore technology belong to the group of factors "Determiners, motors and brakes" (Table 2). They have a powerful impact on the system, essential for long-term trends and future solutions. This suggests a significant difference in the choice of the critical criteria for identifying the location of a CO_2-EGS system. The values of standard deviation of the variable pointing out to on- or offshore technology utilisation (variable no. 14, Table 1) is quite high (Figure 4, row 14). It is caused by diverse experts' opinions about the influence of on- or offshore technology utilisation on other variables. The fact that offshore technology is not common in Poland might help to explain the obtained results. The assessment of the impact of this technology on others could be caused by the lack of experience of Polish experts in this field.

Among the other groups of factors affecting the location of a CO_2-EGS system, the important ones may be those which can be partly controlled. That is the group of "Auxiliary factors". Among those that are essential when locating the system are:

- "Formal constraints" related to a local nature protection area—this variable seems to be very important in the case of an onshore system. For an offshore system, especially located in the area of natural resources, it probably falls outside of any additional formal constraints,
- "Availability of CO_2 sources" (important for both off- and onshore systems),
- "Geological recognition level" (necessary for both systems),
- "The distance of CO_2-EGS from a thermal energy user and electricity grid" (important for both).

It is also important to take note of the other factors that are essential but out of our control. That is the group of "External factors". Their influence is strong, but they cannot be controlled, or can be controlled only partly, e.g., by the selection of the proper location of a CO_2-EGS system. Among this group, as far as system location is concerned, the following seem to be important:

- "Existing wells and other infrastructure",
- "Depth of the EGS system",
- "Water depth" if offshore—its variation is only important in the case of offshore,
- "Physical parameters of reservoir rocks",
- "Reservoir temperature".

Variables noted in the field of "Key factors" indicate activity which should be undertaken or a stage which should tried to reach. In the scope of activity, the variable "Level of the Technological Readiness" indicates that the technology of the CO_2-EGS system has first to be developed and after that continuously improved. The variable "Long term safety of exploitation of the CO_2-EGS system" suggests that the importance of stable and safe exploitation of the system is crucial. That is the goal of its development.

The group referred to as "Results" indicate variables which are slightly influenced by others but also very dependent on them. Among this group, it can be indicated the "Cost of drilling and fracturing". The wide spread of technology might influence the aforementioned cost, as well as the "Cost of energy obtained by the CO_2-EGS system". A practically checked and safe solution might change or settle "Local regulations on the utilisation of geothermal energy" and "Local regulations on CO_2 storage". Clean and renewable energy can gain "Social acceptance for CO_2-EGS".

6. Summary

Based on the research conducted and described in this article, the most essential variables for the development of CO_2-EGS systems technology can be selected, in particular the variables that are important when selecting locations for this type of system. These variables include:

- Formal constraints related to the local nature protection areas—this variable is essential in the case of an onshore system,
- Availability of CO_2 sources,
- Level of geological recognition,
- The distance of the CO_2-EGS from a thermal energy user and electricity grid,
- Existing wells and other infrastructure,
- Depth of the EGS system,
- Water depth if offshore, this variable is only important when offshore systems are involved,
- Physical parameters of reservoir rocks,
- Reservoir temperature.

Author Contributions: Conceptualisation, L.P. and A.S.; methodology, L.P., A.S., P.G., B.T., M.M., T.A. and B.S.F.; software, L.P.; validation, L.P., A.S., P.G., B.T., M.M., T.A., B.S.F. and A.C.; formal analysis, L.P., A.S., B.T., M.M., T.A. and B.S.F.; investigation, A.S., P.G., B.T., M.M., T.A., B.S.F. and A.C.; resources, L.P., A.S., P.G., B.T., M.M., T.A. and B.S.F.; data curation, L.P.; writing—original draft preparation, L.P.; writing—review and editing, A.S., P.G., B.T., M.M., T.A., B.S.F. and A.C.; visualisation, L.P.; supervision, A.S., B.T., M.M., T.A. and B.S.F.; project administration, A.S.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: The research leading to these results has received funding from the Norway Grants 2014-2021 via the National Centre for Research and Development, grant number NOR/POLNOR/EnerGizerS/0036/2019.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data, i.e., the matrices of influences, assessed by each of the experts, are provided at the request of the readers. Each of the readers who want to verify our calculations can use the free MicMac program, available for download at: http://en.laprospective.fr/methods-of-prospective/softwares/59-micmac.html (accessed on 16 December 2020).

Acknowledgments: The results are part of the Polish-Norwegian project: CO_2-Enhanced Geothermal Systems for Climate Neutral Energy Supply, acronym EnerGizerS, registration number NOR/POLNOR/EnerGizerS/0036/2019. The authors would like to thank all the experts involved in completing the research survey.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of important variables indicated by the expert group for CO_2-EGS technology including variables description and additional explanations.

No	Long Label	Short Label	Description/Explanation	Thematic Scope
1	Formal constraints related to a local nature protection area	RestrictEnvLoc	E.g., location within or close to protected areas, environmental restrictions	Environment
2	Current primary energy carrier for heat supply	UsedHeatSource	Primary energy carrier commonly used by surrounding energy users	Environment
3	Quality of air	AirQuality	Air quality, bad air quality suggests that a great deal may be done to improve it	Environment
4	Long term safety when exploiting the CO_2-EGS system	LongThermSafety	Long term safe exploitation of the CO_2 HDR system is important for the environment. This factor is important on a global scale (worldwide) but is crucial on a local scale	Environment
5	Power and energy demand of direct energy user (DHS) [1]	UserP&Q	Direct user of power and energy that is utilising energy for space heating and hot water preparation	Technical
6	Supply temperature requirements of direct energy user (DHS)	UserTemp	The requirement with regard to supply temperature is important in the case of direct energy use. The higher the temperature required, the narrower the range of direct use without additional peak heating. A high supply temperature may also cause a high return temperature and reduce the efficiency of the installation	Technical
7	Availability of CO_2 sources	AvailResCO$_2$	The long-term stability of CO_2 supplies should also be considered as important. Availability of captured CO_2 at proper purity	Technical
8	Availability of cooling water (ground, river, lake, sea)	AvailCoolWater	Cold water is an excellent cooling medium for electricity production. If it lies in the ground, this temperature may not be constant over time until it is used	Technical
9	Level of Technological Readiness	TechReaLev	Level of technological readiness of fracturing, drilling, utilisation of energy carrier. The technology used should be mature	Technical
10	CO_2-EGS system operational parameters	CO_2EGSoperPrm	Inlet and outlet pressure of the EGS system, thermosiphon effect, erosion of the CO_2 components	Technical
11	Availability and stability of time-dependent parameters	TimeDesignPrm	E.g., rapid decrease in the available temperature due to excessive exploitation time due to circulation of fluid. Test regime to identify hydraulic and thermal short-circuits, and thus corresponding preventive actions	Technical
12	Equipment and machinery for supercritical utilisation of CO_2	EandMsCO$_2$	Availability, performance, costs, maturity, etc.	Technical
13	Existing wells and other infrastructure	ExistWells	Presence of existing wells into or near a reservoir. Relevant for reusing old oil and gas reservoirs? Could reduce risk of drilling if one could reuse, and increase risk of leaks	Technical
14	Onshore/offshore	OnOffShore	Offshore sites are probably going to have very different conditions, constraints, and demands	Technical
15	Water depth if offshore	WaterDepthOff	Water depth over the seabed. Affects thermosiphon, technical installations, heat loss to water, etc.	Technical
16	Cost of obtaining CO_2 at a specific location	CO_2Cost	Cost of CO_2 at the CO_2-EGS location (including capture, transport, purification, etc.)	Economy
17	Geothermal system risk insurance fund	GeoRiskInsurance	Drilling, operation, monitoring, maintenance, etc.	Economy

Table A1. *Cont.*

No	Long Label	Short Label	Description/Explanation	Thematic Scope
18	Financial support for CO_2-EGS systems in an early stage of technological development	FinSuppCO_2EGS	Financial support for the preliminary survey and assessment, investment, and operational phase	Economy
19	Accuracy of CAPEX estimate—especially for drilling and fracturing	AccurInestDrillFrac	Drilling and fracturing are the key points. Most investment expenditure is combined with that element. Even a slight error in the investment estimate strongly influences the economic effects. Both depend on the geological conditions, which are uncertain in 100% of cases	Economy
20	CO_2 emission price	CO_2emPrice	EU Emissions Trading System (EU ETS)	Economy
21	Preferable tax discounts	TaxDisc	As the technology is in its early stage, a lot of factors are currently uncertain. If this technology is going to be developed, it needs support at an early stage. Lump sum tax benefits and other governmental support regimes? E.g., direct part financing	Economy
22	Cost of drilling and fracturing	DrilingFractCost	Drilling and fracturing are the most capital intensive factors in the CO_2-EGS system	Economy
23	Price of heat and electricity on the energy market	EnergyActualPrice	Price of heat and electricity produced by other energy carriers	Economy
24	Cost of energy obtained by the CO_2-EGS system	CostOfEnCO_2EGS	The cost of energy obtained by the CO_2-EGS system is one of the most critical factors. One of the goals of this analysis is to detail knowledge on what and how it influences the cost, and to identify risk and cost-reducing factors	Economy
25	Hydrogeochemical information	HydroGeochem	Physical and chemical composition of reservoir fluid, mineralisation of geothermal water, chemical and mineralogical composition of underground rock formations	Geology
26	Availability of other underground resources	AvailOtherResour	Limitations due to the exploitation of other natural resources, e.g., geothermal waters, the possible presence of other minerals, the presence of underground water reservoirs of strategic importance	Geology
27	Geological recognition level	GeolRecog	Geological risk. The certainty of the local geological structure, the quality of its recognition, the vicinity of boreholes, access to geophysical surveys. Availability of geological and geophysical data. Geophysical data (3D Seismic data)	Geology
28	Physical parameters of reservoir rocks	RocksPhysicPrm	Thermal conductivity coefficient, specific heat. Geomechanical properties of reservoir rocks. Homogeneity/heterogeneity of geological setting. Porosity and permeability of rock in natural reservoir	Geology
29	Presence and distribution of natural faults and fractures	FractPres&Distr	Information on existing natural fractures of rock (double-porosity model), tectonic stress regime	Geology
30	Potential for hydraulic stimulation (fracturing) of the geological formation	PotentFract	Hydraulic fracturing technology—predictability of parameters of the fracture zone. Rock stress measurements	Geology
31	Natural seismicity at the EGS site	Seismicity	The natural seismicity at the EGS site is crucial for the safety of the installation. Appearance of an additional and uncontrolled fracture might make the system open to CO_2 migration	Geology
32	Stratigraphy and lithology, geological structure	Strat&Lithology	Presence of overlying cap rock, stratigraphic trap, suitable geological structure	Geology

Table A1. *Cont.*

No	Long Label	Short Label	Description/Explanation	Thematic Scope
33	Reservoir temperature	TempResources	The reservoir temperature limits the potential ways of obtaining energy from it (direct, indirect use), its power, and the energy production. The higher the temperature, the more comprehensive the opportunity but the more challenging the working conditions in the system from a technical point of view	Geology
34	Hydrogeological conditions	HydrogolCondition	The hydrogeological connection between the reservoirs and the surrounding environmental components (other reservoirs, atmosphere, etc.). Risk and detection of any hydraulic and thermal short-circuits	Geology
35	Depth of the EGS system	DepthEGS	Depth at which the geological formation, the use of which is assumed for the EGS system, is located. The depth influences the temperature (increases it) but also increases the investment expenditure	Geology
36	Thickness and tightness of isolating overburden	CapRock	Type of cap rock, its thickness and tightness. Those parameters are crucial for the safe exploitation of the system	Geology
37	Thickness of reservoir	ThicknessRes	The thickness of the reservoir limits the volume of the fracture zone. The higher the volume available for fracturing, the higher energy potential of the system and more stable the parameters even when the flow rate of the working (CO_2) fluid is high	Geology
38	The distance of the CO_2 EGS from a thermal energy user and electricity grid	DistanceGrid	Distance between the CO_2-EGS and the energy grid and consumers. A long-distance generates a higher investment expenditure and causes high thermal energy losses and electricity consumption (pumping), but increases the local safety of the users	Transportation and logistics
39	The degree of urbanisation of the area	UrbanArea	The degree of urbanisation of the area might influence in a positive way (short distance to the user) and in a negative (high price of land, limitation due to urbanised surroundings)	Transportation and logistics
40	Access to surface infrastructure	AccessSurfaceInf	Access to roads, a sufficiently large area of land for drilling and construction works	Transportation and logistics
41	Qualified personnel for the development and operation of CO_2-EGS	ManPower	The availability of professional manpower	Social
42	Social acceptance of CO_2-EGS	SocialAcceptEGS	Social acceptance of CO_2-EGS is crucial. Inhabitants in the surrounding area should know the advantages and disadvantages of this technology. They should be well informed	Social
43	Good practice and examples of utilisation of geothermal energy	GoodPractGeoHeat	Local experience of geothermal exploitation. Use of international experts.	Social
44	Energy security and policy	EnergySecurity	Energy security at a governmental or local level. The recognition of policy and the legal framework for the technological option. Is CO_2-EGS a part of the energy policy in the given country? Political stability—predictability of supporting regimes	Legal and policy
45	Local authority interest	AuthInterest	Interest and support from local authorities, risk aversion	Legal and policy
46	Local regulations on the utilisation of geothermal energy	LocalRegulatGeo	Local regulations on the utilisation of geothermal energy influence the CO_2-EGS system	Legal and policy

Table A1. *Cont.*

No	Long Label	Short Label	Description/Explanation	Thematic Scope
47	Local regulations on CO_2 storage	LocalRegCO_2stor	Local regulations on CO_2 storage (EU or national level)	Legal and policy
48	Land ownership type (private ownership, local government ownership)	LandProperty	Terrain accessibility for EGS and surface site. Terrain accessibility for CO_2 piping infrastructure	Legal and policy

[1] DHS—District Heating System.

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