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Predictive Model for History Matching of Social Acceptance in Geothermal Energy Projects

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ABSTRACT

One of the biggest challenges in developing renewable energy, such as geothermal energy, is understanding how to be accepted by the community impacted by the development. However, very few studies attempted to numerically express the time-dependent process of social acceptance in renewable energy projects. We quantify how social acceptance for a geothermal energy project is acquired from the involved communities. First, we present a compartment model for simulating how the numbers of supporters and opponents of developing geothermal energy change over several decades. We then introduce a time-varying index, an effective susceptibility number (R_e), similar to the effective reproduction number used in modeling epidemiologic phenomena. Second, we share our findings about the history of the number of supporters and opponents of the geothermal power plant construction project in Japan based on the articles published in local and national newspapers between 1970 and 2020. Our simulation results show that the proposed compartment model could predict documented changes in the numbers of supporters and opponents. Also, the effective susceptibility number (R_e) could represent the frequency of interactions among the community members. We suggest that an effort should be made to avoid having $R_e < 1$ in the community, to maintain a steady increase in the number of supporters to eventually acquire the social acceptance of a geothermal energy project. Our simple but novel approach using the compartment model will help better understand the dynamics and predict the community acceptance process in geothermal and other renewable energy projects.

Introduction

Social acceptance is one of the most important factors for predicting the successful dissemination of newly introduced products, services, systems, and practices [1]. For example, the level of social acceptance in a renewable energy project should be understood as a result of a series of decision-making processes [2-4]. When promoting an energy project, we should first understand the level of the will in the community for sustainable development and then the various benefits for the community [5]. Trust among the people in the community makes them feel positive about their participation throughout project development [6,7]. The importance of acquiring social acceptance from the community has been extensively studied for developing projects for renewable energy [8-11], biofuel [7,12,13], green electricity [14], carbon capture and storage [15], and green products [16]. Previous studies employed numerical simulations to investigate social acceptance in various energy-related fields through tailored numerical modeling strategies. For example, agent-based modeling has been used to investigate the dynamics of bottom-up processes of acquiring social acceptance by incorporating the characteristics of agents [17-20]. An earlier study [17] focused on the local interplay among community members without giving specific attention to known historical events. The agent-based modeling is particularly suitable for understanding social phenomena where no mathematical equations can adequately describe the processes [21-23]. Also, Cayir Ervural et al. [24] provided a multi-objective decision-making model for renewable energy planning by implementing the social acceptance factor using fuzzy logic. However, most of the proposed models have not been able to adequately express the changes in the number of social acceptance with time, because they generally accompany several issues regarding temporal and spatial scales that are seemingly unsolvable. Social acceptance of renewable energy should be studied more time-dependently as it represents a time-variable dynamic process [3,25].

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Nomenclature

Abbreviations

LLC	Limited liability company

Symbols

$A(t)$	Number of individuals in the compartment A at time t
$E(t)$	Number of individuals in the compartment E at time t
i	Average period for an individual to determine to further supporting the project
ℓ	Average period for an individual to agree with the project
N	Total number of the individuals
$O(t)$	Number of individuals in the compartment O at time t
$R_e(t)$	Effective susceptibility number at time t
$R_0(t)$	Susceptibility number at time t
R_0^a	Constant susceptibility number at $1970 \le t < 2002$
R_0^b	Constant susceptibility number at $2002 \le t < 2011$
R_0^c	Constant susceptibility number at $2011 \le t \le 2020$
$S(t)$	Number of individuals in the compartment S at time t
t	Time
γ	Inverse of the average period i
σ	Inverse of the average period ℓ

Research in the process of geothermal energy development can provide many interesting opportunities. Geothermal is a renewable energy resource; however, its development requires drilling just as oil and gas resource development does. Residents in the geothermal development area play the most significant role in transforming sustainability perceptions into tangible experiences [26], fostering social acceptability and motivating socio-technical change for geothermal projects. In the Tolhuaca geothermal project in Chile, the project was eventually canceled partly due to stakeholders' perceptions that were influenced by project developers, local stakeholders, and the contextual factors relating to the dimensions outside the project [27]. Also, developing enhanced geothermal systems could induce seismicity through fluid injections in the development sites, occasionally occurring large earthquakes of up to a Moment magnitude of 5.5 [28-30]. In European counties, many geothermal projects have been socially accepted, although there are still some projects that are concerned with induced risks, environmental issues, local politics, and sovereignty [31-34]. Therefore, social acceptance from the local community must be thoroughly considered to achieve the geothermal projects.

After the Tohoku-Oki Earthquake and the Fukushima nuclear accident in 2011, there has been a growing demand to accelerate the development of geothermal energies in Japan due to the closure of most of the existing nuclear power plants [35,36]. However, many hot springs are tied culturally and economically to local communities, and geothermal resources are often co-located. Thus, geothermal projects often raise concerns about the depletion of hot spring water. These concerns often put geothermal projects on hold. Kubota et al. [35] suggested that the uncertainties with the longevity of hot spring resources lead to the low acceptance of geothermal power projects. Many geothermal power projects lacking social acceptance have experienced strong opposition from nearby residents (Table 1). To avoid or mitigate the strong opposition, geothermal resource developers should constantly engage local stakeholders, including, most importantly, the community. This improves their understanding and cooperation while minimizing environmental impacts and landscape transformations in the given geothermal area [37,38]. Therefore, frequent dialogue and interactions among the community stakeholders, residents, and local government are among the most significant factors determining the eventual acquisition of social acceptance for a geothermal project.

Table 1
Oppositional movements to Japanese geothermal power projects before 2010. Modified from refs [39,40].

Year	City/Town	Project Site
1981	Kusatsu & Tsumagoi, Gunma Pref.	Piedmont district of Mt. Kusatsu-Shirane
1981	Beppu, Oita Pref.	Garandake Area (Beppu City & Yufu City)
1983	Shuzenji, Shizuoka Pref.	Amagiyugashima Town (Currently Izu City)
1983	Gero, Gifu Pref. / Otaki, Nagano Pref.	Piedmont district of Mt. Ontake
1992	Hachimantai, Iwate Pref. / Kazuno, Akita Pref.	Kazuno City
1996	Oguni, Kumamoto Pref.	Oguni Town
1996	Toyoha & Jozankei, Hokkaido Pref.	Jozankei Onsen Area
2002	Kirishima, Kagoshima Pref.	Makizono Town (Currently Kirishima City)
2004	Obama & Unzen, Nagasaki Pref.	Obama Town (Currently Unzen City)
2007	Ibusuki, Kagoshima Pref.	Ibusuki City
2008	Kusatsu & Tsumagoi, Gunma Pref.	Tsumagoi Village

Very few studies attempted to numerically express the time-dependent process of social acceptance in geothermal energy projects on an exact time scale. Constructing the time-varying numerical model helps understand the factors most significantly determining the social acceptance process in the geothermal project. The mathematical model will also help recreate history and predict future trends in the given community and project. Thus, this study aims to develop a numerical model to quantify the process of how a local community acquires social acceptance for geothermal resource development with time. First, we construct, for the first time to our knowledge, a simple compartment model for simulating how the numbers of supporters and opponents for a given geothermal project change with time over several decades. We also define a time-varying index, effective susceptibility number (R_e), which is inspired by the effective reproduction number used as an epidemiologic metric. Second, we obtain the history of the numbers of supporters and opponents of the geothermal power plant in a local community in Japan from articles in old newspapers. We examine whether our simple compartment model can reconstruct the change in the numbers of supporters and opponents obtained from newspaper articles through parametric studies. We then suggest that our new time-varying metric, effective susceptibility number (R_e), can represent well the level of opinion exchanges or the frequency of dialogue and interactions within the community for a geothermal energy project.

Historical Data and Simulation Method

Reconstruction of history from newspaper articles and interviews

Japan, a volcanic island, is blessed with geothermal energy resources and thus should be more engaged in developing geothermal energy. However, developing a geothermal power plant has sometimes drawn unfounded fear of depletion from the local hot spring community, resulting in opposition movements in the local district in Japan (Table 1). We selected the town of Oguni in Kumamoto Prefecture, Japan, as an example for this study because this town, after much struggle, obtained social acceptance from the community to successfully develop a geothermal power plant (Fig. 1). The company J-POWER (Electric Power Development Company Ltd., Japan) first led the exploration of geothermal resources in the area in the early 1980s [41]. As part of a Japanese governmental project, the studied area had previously initiated a plan for developing a geothermal power plant as early as the 1970s. The effort of a small group of community members resulted in supporting the project from the local community but not until after the 2011 Fukushima nuclear disaster. For this study, we needed documents that indicated changes in the numbers of residents supporting and opposing the development of a geothermal power plant. We, therefore, collected the old articles from a local newspaper Kumamoto Nichinichi Shimbun (lit. "Kumamoto Daily Newspaper") and a national newspaper Nihon Keizai Shimbun (lit. "Japan Economics Newspaper"), published between 1970 and 2020, available from the Japanese digital online newspaper database at the Kumamoto Prefectural Library. By searching with the three Japanese keywords "Geothermal," "Hot springs," and "Oguni" using the search engine of the newspaper database, we found 41 articles that helped us understand the changes in opinions about the geothermal project in Oguni. We further interviewed the people in the community about the history of geothermal development to corroborate the changes that were available from the newspaper articles. By compiling these findings, we could reconstruct the changes in the numbers of proponents and oppositions for the geothermal project in the studied community.

Our data on the shift of people's opinions are primarily based on the published newspaper articles as the town of Oguni, like many other mountain communities in Japan, has been facing a population decline, and it was a considerable challenge to collect unbiased opinions about the changes that took place many years ago. We did not identify any polls taken by newspapers that could help who exactly agreed or opposed the geothermal project and their socio-demographic profiles (e.g., ages, family size, education levels, occupations, household incomes) that often have a profound effect on social acceptance [10,42]. We note that data gathering from communities like Oguni will be further challenging in the future for any researchers. As data gathering becomes more difficult, there is a need for a robust mathematical model that can recreate past history and help predict future trends. We have decided to use a compartment model to understand the flow of information between the groups. Because such data on the history of numbers of individuals were not reported in most previous papers, our data help not only this study but also implement to machine and deep learning to better understand the social acceptance of renewable energy projects.

Compartment model

The goal here is to develop a simulation model that can predict how people in a community can change their opinions about a geothermal energy project using the simplest parameterizations. A compartment model is well suited for our objectives as it is a mathematical model that can describe the flow of information between "compartments" in the closed system, i.e., a community with a fixed population (e.g., [43–45]). Inspired by the effort in the development of mathematical models for the spread of pandemic diseases (e.g., [46]), our compartment model consists of four compartments: the opposition component O, the exposed component E, the agreed component A, and the supporting component S within the community (Fig. 2). In our model, what flows between compartments is the opinions of individuals within the community. Thus, people's opinions and factors outside the project, which can often be essential to determine the eventual social acceptance [27], were not considered. The component O contains the individuals who are against the geothermal energy project. The compartment E contains the individuals that are contemplating whether to change their opinions to support the project but have not yet committed. We assume that the individuals in the compartment O who are thinking of accepting the project can only move to the compartment E, but they do not actually need to change their opinions. Individuals can move from one compartment to the next without actually changing the level of their opinions. The compartment A contains the individuals that can endorse the project. They can

Fig. 1. Studied community of geothermal area of the town of Oguni in Kumamoto Prefecture, Japan, that acquired eventual social acceptance for a geothermal project. Photo taken by authors in July 2019.

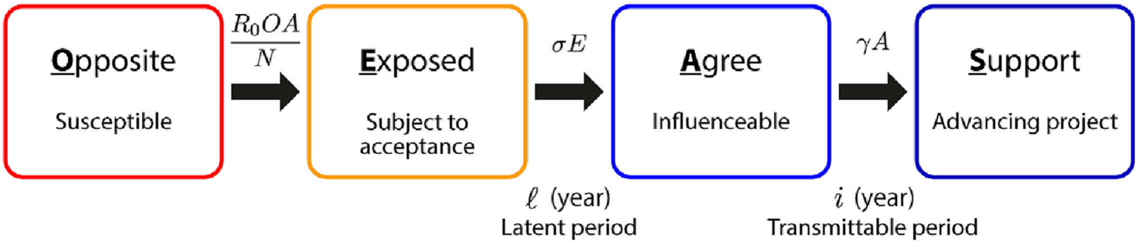

Fig. 2. Schematic representation of the flow of individuals between four classes in our compartment model.

change their minds to further support the project. The compartment S contains the individuals that fully support the advance of the project. Our compartment model assumes that individuals are in one of the four compartments O, E, A, and S.

We construct a simple compartment model that can describe changes in the number of individuals in each compartment:

$$\frac{dO(t)}{dt} = -\frac{R_0(t)\,O(t)\,A(t)}{N} \tag{1}$$

$$\frac{dE(t)}{dt} = \frac{R_0(t)\,O(t)\,A(t)}{N} - \sigma E(t) \tag{2}$$

$$\frac{dA(t)}{dt} = \sigma E(t) - \gamma A(t) \tag{3}$$

$$\frac{dS(t)}{dt} = \gamma A(t) \tag{4}$$

where $O(t)$, $A(t)$, $E(t)$ and $S(t)$ are the numbers of individuals in the compartments O, A, E and S at time t (year), respectively, and the total number of the individuals $N = O(t) + E(t) + A(t) + S(t)$ is fixed. The coefficients σ and γ in equations (2) through (4) are respectively defined as $\sigma = 1/\ell$ and $\gamma = 1/i$, where ℓ (year) and i (year) are the average period for an individual to agree with an energy project ("latent period") and the average period for an individual to determine to further supporting the project ("transmittable period"), respectively. We refer to the number $R_0(t)$ as the susceptibility number. In a simple sufficient cause model in epidemiology, the term susceptibility is defined as the underlying set of factors sufficient to make a person contact an infectious disease following the exposure [47-50]. The fraction $A(t)/N$ is the probability of a random contact with an individual in compartment A in a population size of N, and thus the number $R_0(t)O(t)/N$ is the number of individuals that change their compartments from O to E motivated by one person in compartment A. The individuals in compartments E and A change their class to classes A and S at the rates of σ and γ, respectively (Fig. 2).

The susceptibility number $R_0(t)$ assumes a population that is susceptible to changing people's opinions based on a set of underlying factors. In our simulation, the susceptibility number $R_0(t)$ is given as a fixed value during a given time period (see Section 3.2). In addition to the susceptibility number $R_0(t)$, we now define a time-dependent effective susceptibility number $R_e(t)$, which is analogous to the effective reproduction number used as an epidemiologic metric [49,51,52]. The newly introduced effective susceptibility number is computed by the product of the fixed susceptibility number $R_0(t)$ and the fraction of the host population that is susceptible to changing their opinion to agree with the project at the time. The effective susceptibility number $R_e(t)$ can thus be expressed by:

$$R_e(t) = R_0(t) \times \left(1 - \frac{A(t) + S(t)}{N}\right) \tag{5}$$

Results and Discussion

Literature and interview survey

From the digitally archived database of the Japanese newspaper, we found 41 articles published in the two newspapers, Kumamoto Nichinichi Shimbun and Nihon Keizai Shimbun, between 1970 and 2020 that helped quantitatively understand the changes in the individuals who supported and disagreed with the geothermal project in the studied community (Fig. 3). There were 33 articles published between 1970 and 2002 and 8 articles between 2012 and 2020. We could not identify any individuals who could potentially be in compartment E throughout the studied period because there was a lack of clear evidence from the newspaper articles and interview records. The newspaper article suggested that all the involved individuals, in principle, did not favor or at least did not consider the successful geothermal project in 1970; however, we could not determine the exact number of individuals who agreed and opposed the project in 1970. Thus, we counted that all the involved individuals within the community opposed the geothermal project in 1970, although this initial condition in 1970 should have some uncertainty. The interview survey revealed that there were a couple of stakeholders at the beginning of the study period, suggesting that at least a few or more individuals within the community could agree or support the project. Concerns about the hot spring depletion had amplified since the winter of 1994. No individual supported the geothermal power project in the early 1970s, except for a couple of external stakeholders, when the company J-POWER initiated the geothermal project. A total of 11 articles appeared between 1996 and 1997 when the opposition to the geothermal project intensified. The article from Kumamoto Nichinichi Shimbun reported in July 1997 that nine individuals in the community showed their strong opposition to the geothermal project, resulting in the closure of the geothermal power plant project led by J-POWER. Our literature survey also found that the number of individuals who opposed the project gradually decreased between 2000 and 2002. There was no article published between February 2002 and 2011. This period of 10 years is exactly the duration in which the studied community experienced continuous community division and eventually called off a traditional summer festival that had taken place every summer for more than 700 years. Later, however, the change in the energy landscape in Japan due to the Fukushima nuclear disaster in 2011 significantly changed the attitude of the community and reopened the discussion of the geothermal project. The town of Oguni subsequently launched a limited liability company (LLC) in 2011 to promote geothermal development. The Oguni town eventually acquired a strong community acceptance for the geothermal project in 2015–2016. These facts suggest that respecting all the residents with their own culture and traditions and involving them in a core part of the project are essential to acquiring their social acceptance leading to the successful promotion of the geothermal project.

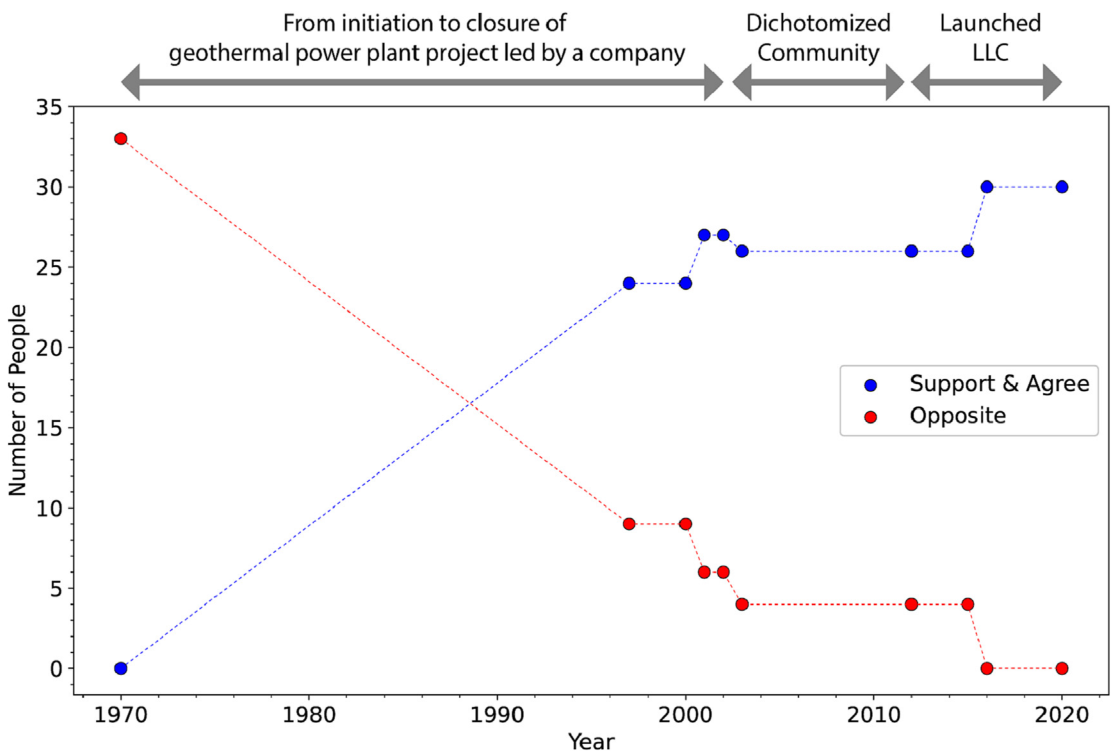

Fig. 3. Observed changes in the individuals opposing and agreeing/supporting the geothermal project in the studied district.

From our newspaper records, we could identify the three distinct periods based on the support level of opinion exchanges within the community; 2011–2020, 1970–2002, and 2002–2011 from higher to lower exchange levels. It should be noted that the total number of identified individuals decreased from 33 to 30 between 2002 and 2011, mostly due to depopulation.

Very few papers reported the data on the history of the number of individuals who agree and oppose a renewable energy project. Our history data over 50 years, yet the two decades of data unavailability within the studied period and some uncertainty in the initial condition, will be among the first-ever most quantitative time-series data for the process of the social acceptance of the renewable energy project. Thus, we believe that the obtained data are valuable in better understanding the social acceptance of renewable energy projects. The time-series data, like our obtained data, can also help implement machine and deep learning to better understand the processes and complexities of social acceptance of renewable energy projects when more data from various renewable energy projects are available.

Compartment model simulation

We used the proposed compartment model to study the changes in the number of supporters and oppositions for the period of 50 years (1970–2020) and compared the predicted changes with the actual changes as observed in Section 3.1. Because we could identify the three distinct periods of time that could be characterized by different levels of residents' opinions within the studied community (see Section 3.1), we consider the susceptibility number that varies with the three different periods as:

$$R_0(t) = \begin{cases} R_0^a, 1970 \leq t < 2002, \\ R_0^b, 2002 \leq t < 2011, \\ R_0^c, 2011 \leq t \leq 2020, \end{cases} \tag{6}$$

where R_0^a, R_0^b, and R_0^c are all constant susceptibility numbers in each time period. Here, the susceptibility numbers should satisfy $R_0^c \geq R_0^a \geq R_0^b$, because our observations revealed that exchange levels of opinions in 2002–2011 and 2011–2020 were respectively lowest and highest, as mentioned in Section 3.1. Also, the first susceptibility number should satisfy $R_0^a \geq 1$ because the number of individuals in compartment O decreased significantly between 1970 and 2002. As for the inverse of the average period for an individual to agree with the project ($\sigma = 1/\ell$) in the studied case, we chose $\sigma = 1/10$ (1/year) as evidenced by our observation that the community split could continue for 10 years in the studied community (Section 3.1). The initial conditions for the numbers of individuals in 1970 were basically from our observations in Section 3.1. However, we assumed the individual of compartment E was zero in 1970 because we could not identify the exact number from our observations. Also, we added two individuals in compartment A in 1970. This is because the number of $A(t) + S(t)$ does not change with time when the initial value of $A(t)$ is zero in our compartment model and we recognized a couple of stakeholders at the beginning of the studied period from interview surveys (Section 3.1). In this study, we simplified the inverse of the average period for an individual to determine further supporting the project ($\gamma = 1/i$) to $\gamma = 1$ (1/year). This is because we presumed that the transmittable period (i) should be much shorter than the latent period (ℓ) based on our interview record, although we could not classify the compartments A and S separately. Using these parameter settings, we performed simulations with different combinations of three susceptibility numbers $\left(R_0^a, R_0^b, R_0^c\right)$ to study the changes in $O(t)$ and $A(t) + S(t)$ between 1970 and 2020.

Our simulation results demonstrate that the temporal changes of the numbers $O(t)$ and $A(t) + S(t)$ during 1970–2002 can be highly variable when changing the susceptibility numbers R_0^a between 1.0 and 5.0 (Fig. 4). When $R_0^a = 1.0$, the numbers $O(t)$

and $A(t) + S(t)$ show a slight linear increase and decrease, respectively, and deviate significantly from the observed changes. In contrast, the numbers $O(t)$ and $A(t) + S(t)$ with the highest susceptibility number of $R_0^a = 5.0$ show a more rapid drop and rise than those of the observed changes. When $R_0^a = 2.5$, our model may demonstrate well the change in the number of compartment $O(t)$ in 1996 – 2002 but underestimates the change $A(t) + S(t)$. We thus suggest that our model can generally predict observed changes when the susceptibility number in 1970–2002 is $R_0^a = 3.0$ (Fig. 4). However, it is difficult to conclude what susceptibility value best fits them because their data are unavailable between 1971 and 1996, and the modeled change of compartment $O(t)$ underestimates significantly between 1996 and 2000 (Figs. 3 and 4). Also, determining the second susceptibility number R_0^b is somewhat arbitrary due to the lack of sufficient data points between 2002 and 2011. The susceptibility number R_0^b can be close to zero because the studied community was subject to community split, but at the same time, it must be nonzero as there could have been more than a few interactions within the community providing any chances of acquiring susceptibility. In contrast, the third susceptibility number R_0^c is guessable given the control points available between 2011 and 2020. The basic susceptibility number R_0^c should be the highest among the three basic susceptibility numbers $\left(R_0^a, R_0^b, R_0^c\right)$ given that the studied community advanced much in the geothermal project, and thus we found $R_0^c = 30$ was the most reasonable (Fig. 4).

Effective susceptibility number and its interpretations

We determined the set of three susceptibility numbers $R_0(t) = \left(R_0^a, R_0^b, R_0^c\right)$ in our compartment model that best reconstructed the observed changes in the studied community as shown in Section 3.2. We found that the set of susceptibility numbers $\left(R_0^a, R_0^b, R_0^c\right) = (3, 0.1, 30)$ best explained the observed changes in our case study (Fig. 4). However, the susceptibility number $R_0 = \left(R_0^a, R_0^b, R_0^c\right)$ is time-independent throughout the given defined period. This simply represents the average number of susceptible individuals under the assumption that all individuals are susceptible at the beginning of a geothermal power project, as suggested from the basic reproduction number used in epidemiology [48,49].

On the contrary, the newly defined effective susceptibility number $R_e(t)$ is truly time-dependent throughout the studied period and better represents variations in transmission potentials while taking into account the decline in susceptible individuals. Using equations (5) and (6), we can see the temporal changes in the effective susceptibility number $R_e(t)$ with different sets of susceptibility numbers $\left(R_0^a, R_0^b, R_0^c\right)$ during the studied period 1970–2020 (Fig. 5). For example, when the susceptibility numbers are $\left(R_0^a, R_0^b, R_0^c\right) = (3.0, 0.1, 30)$, the effective susceptibility number $R_e(t)$ gradually decreases from 2.8 to 0.7 during 1970 and 2002, drops to 0.02 in 2002–2011, and then rises to 4.6 in 2011. The effective susceptibility number $R_e(t)$ falls gradually to below 1.0 by 2002, in any possible scenarios with the first susceptibility number of $R_0^a > 1$. This well reflects that the period eventually resulted in the closure of the geothermal project and the interruption of opinion exchanges within the community in 2002. The effective susceptibility number $R_e(t)$ during 2002 and 2011 is extremely low, in the order of magnitude of around 10^{-2}, representing very few opinions exchanged within the community due to the community split. In 2011, however, the effective susceptibility number $R_e(t)$ climbs up to the highest values in most of the choices of the third susceptibility number R_0^c. This elevation can explain reopening the opinion exchange within the community leading to full social acceptance of the geothermal project. We thus suggest that the effective susceptibility number $R_e(t)$ is a useful time-varying measure that represents and quantifies the different levels of individual interactions within the community.

Moreover, in our study, we found that the effective susceptibility number $R_e(t)$ in most of the scenarios gradually decreased and reached 1.0 in 1996–1998, which is the exact period when the opposition to the geothermal project intensified in the studied community (Section 3.1). The effective susceptibility number $R_e(t)$ was further decreased to 0.7–0.8 in most of the cases in 2002 when the closure of the geothermal project led by a company was discussed. It subsequently fell to and remained at the order of magnitude of 10^{-2} during the period of the community split. These suggest that the local community needs to avoid having the effective susceptibility number of $R_e(t) < 1$ for maintaining the suffi-

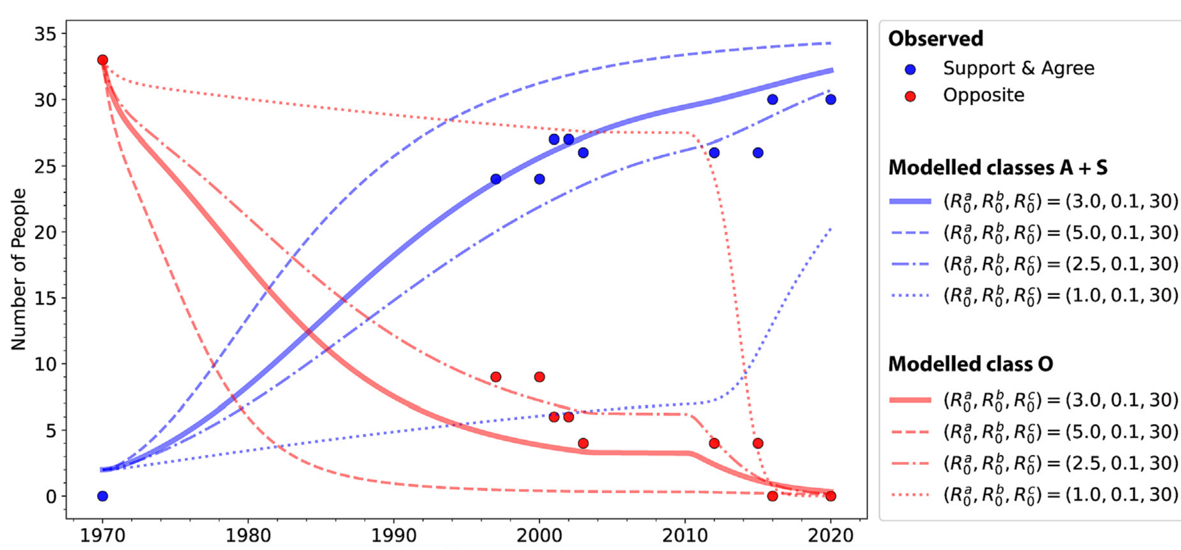

Fig. 4. Observed changes (solid circles) and modelled changes (solid, dashed, dash-dotted and dotted lines) in $O(t)$ and $A(t) + S(t)$ with different choices of susceptibility numbers $\left(R_0^a, R_0^b, R_0^c\right)$.

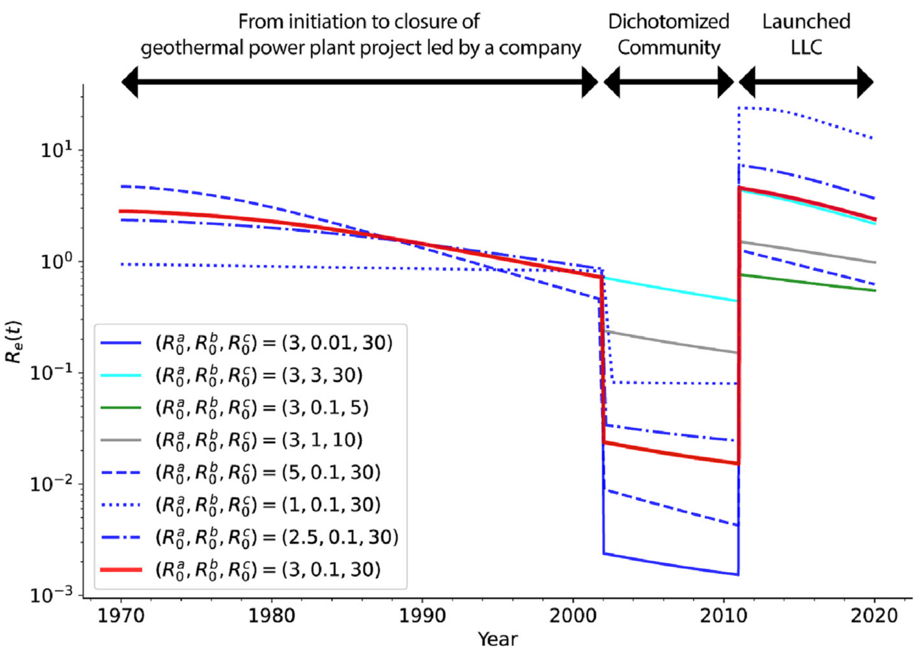

Fig. 5. Changes in the effective susceptibility number $R_e(t)$ with time t.

cient frequency of dialogue and interactions within the community and a stable increase in the number of supporters to successfully acquire the full social acceptance of the project. Among the most important for avoiding $R_e(t) < 1$ should be respecting all the residents with their own cultures and traditions and explaining all pros and cons to them openly and in-depth.

Limitation of our compartment model

We found that our compartment model could reconstruct the changes in the number of individuals in the compartments O, A, and S. Also, the newly defined time-dependent effective susceptibility number $R_e(t)$ documents the way individuals interact with each other within the community. This study aimed at modeling the change in the number of individuals in compartments O, A, and S using as simple and generic parameterizations as possible. Thus, we recognize that our approach can still be modified in further studies. For example, in our model case, 33 individuals were recognized within the community before the early 2000s, although the total number of individuals decreased to 30 during 2002–2011 because of the population decline in the studied community. However, our model cannot implement the changes in the total number of individuals because our studied compartment model assumes that the total number of involved individuals is constant. During the span of 50 years of history matching, this assumption was too rigid as the community members were aging. It should also be noted that the average period for an individual to agree with the renewable energy project ℓ (year), which depends on the studied community, can significantly vary the changes in the number of each compartment. For example, the numbers $O(t)$ and $A(t) + S(t)$ can dramatically change within 10 years when $\ell = 1$ (year), while their changes are small when $\ell = 20$ (year), twice the value estimated in our model case (Fig. 6). The change in $O(t)$ with $\ell = 1/\sigma = 15$ (year) better fits the observed change in compartment O, although the prediction with $\ell = 15$ (year) underestimates the change in $A(t) + S(t)$ and we constrained as $\ell = 10$ (year) by our observations in the studied case. Therefore, we need to appropriately evaluate the average latent period $\ell = 1/\sigma$ that might cause large uncertainty in quantifying the changes in the number of given compartments. The average latent period $\ell = 1/\sigma$ can be better constrained when the data of change in compartment E are available.

Nevertheless, one of the distinct advantages of our approach is that our model can investigate time-dependent problems more properly than other models do. Most of the proposed models, such as agent-based modeling and applications of the game and network theories, are not well equipped to deal with time-varying processes appropriately because they should mostly rely on several assumptions on the temporal and spatial scales [21-23,45]. Moreover, our model can provide a possible number of individuals who can potentially be component E that are not generally identified by literature and interview surveys. However, in contrast to agent-based modeling used in numerically investigating the social acceptance of advancing energy projects [17-20], our compartment model cannot take into account the characteristics of individuals that can influence the opinion levels differently. Individual family members should also be expressed differently from the four primary compartments proposed in our model. Thus, our simulation result alone cannot explain what are exactly the factors that primarily influence the changes in the number of given individuals. Also, whereas the effective susceptibility number $R_e(t)$ helps infer the frequency of dialogue and interactions within the community, our method may not allow interpreting what kinds of interactions occur throughout the given social acceptance process. Moreover, our case study represented a small sample size and could not well define the attitudes and educational levels of the individuals and exactly who agreed and opposed the given project from newspaper articles. Our compartment model is thus still incapable of dealing with these factors, likewise most of the other approaches provided in the previous studies. Consensus changes, attitude changes in groups, and complexity must be the essential factors affecting the processes of social acceptance [27,53,54], although our simple compartment model assumes identical individuals within each compartment. Anyhow, combining our compartment model with the agent-based modeling or modifying our compartment model by appending more multi-compartments that individually repre-

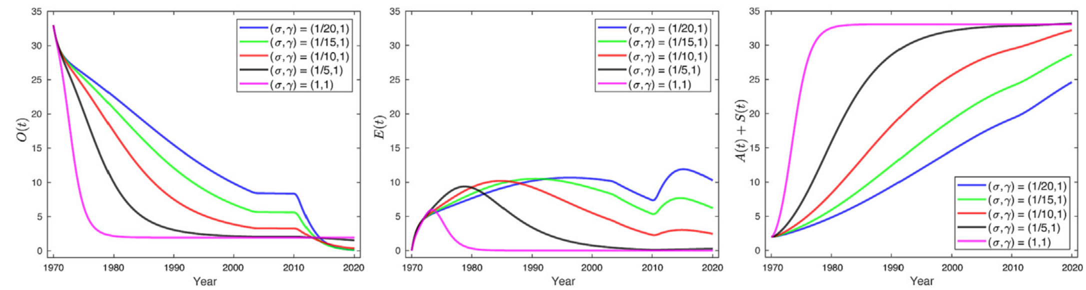

Fig. 6. Changes in the numbers of $O(t)$, $E(t)$ and $A(t) + S(t)$ with the different values of parameter $\sigma = 1/\ell$, where $\ell = 1, 5, 10, 15, 20$ (year). All the computations were done with the set of three susceptibility numbers $\left(R_0^a, R_0^b, R_0^c\right) = (3, 0.1, 30)$.

sent different influence levels will make our approach a powerful tool for understanding the acquisition process of social acceptance for advancing renewable energy projects.

Conclusions

We attempted to quantify the time-dependent process of how the local community acquires social acceptance for a geothermal energy project. First, we obtained the history of the number of proponents and opponents of geothermal power plant development in a local community in Japan from published newspaper articles and interview surveys. Second, we proposed a novel compartment model for simulating how the numbers of proponents and opponents change over time. The literature and interview surveys revealed that involving residents in a part of the project is essential to acquiring their social acceptance leading to a successful geothermal project. The simulation results showed that the proposed compartment model could reconstruct the change in the numbers of supporters and opponents between 1970 and 2020, obtained by compilation from old literature and interviews. Our simulation further suggested that a time-dependent effective susceptibility number $R_e(t)$ could represent the changes in the opinions or the frequency of dialogue and interactions within the community for a geothermal project at the time. We suggest the local community needs to avoid having the effective susceptibility number of $R_e(t) < 1$ to ensure a stable increase in the number of supporters to eventually acquire the social acceptance of a geothermal energy project. Among the most important for achieving it should be respecting all the residents with their own cultures and traditions and explaining all pros and cons to the community openly and in-depth. Although further improvements are necessary, our compartment model is applicable to any communities facing geothermal projects and provides the first-order quantification of changes in people within the community opposing and agreeing with the geothermal development. The proposed new approach will help better understand and predict the process of community acceptance in not only geothermal resource development in any geothermal region but also other clean energy developments.

CRediT authorship contribution statement

Yuya Komori: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization. **Arata Kioka:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft. **Masami Nakagawa:** Funding acquisition, Resources, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available upon request.

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