Smart Resilience Engineering: Mitigative Planning of Networked Infrastructures, Uncertainties and Robust Management

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Introduction

At present, *systemic supply risks* in a future smart urban world, where networking, automation and complexity of infrastructure systems have increased, can hardly be quantified reliably [1]. Part of this uncertainty is that the long-term steady planning and reliable operation of sustainable energy systems, which depend on volatile renewable decentralized feed-in, are based, among other things, on regional climate or weather forecast models. However, the further we look into the future, the more uncertain these are.

For instance, an additional bulk demand for electricity for the use of cooling systems associated with a heatwave [2] can lead to supply bottlenecks and overloads of renewable distribution and transmission grids, ultimately causing large-scale blackouts. The resulting failure cascades in highly networked and automated or electrified systems [3] may lead to considerable supply failures of systemic proportions and significantly reduce the performance of complex *critical infrastructure systems* as typically existing in urban environments. If resilience is not integrated into a system design, renewable energy systems run risk to fail in the long-term. Thus, sustainability and resilience are thought together; this working group develops new methodologies and concepts for identifying resilient planning patterns and smart management systems for adaptive and autonomous energy grids resp., establishes systemic risk assessment frameworks and early-warning concepts, and furthermore designs decision support systems for smart crisis management in complex multi-stakeholder environments.

These research topics belong to the emerging field of ‘Smart Resilience Engineering’, which leverages lived principles and long-standing expertise of this working group: JRODOS is a decision support system for nuclear emergency management, which has been developed and hosted by this group for many years and is operationalized in more than 40 countries worldwide. However, the gain in knowledge in nuclear emergency management over the last decades is not yet at an end, as on a global level, it can be assumed that nuclear power generation is more likely to be expanded in order to achieve climate targets, and therefore, for example, in the case of Small Modular Reactors (SMRs), which would also be installed close to cities and dense *critical infrastructure systems*, research on the safety of SMRs and emergency protection must be adapted to new siting concepts.

An example of the synergetic effects is the MCDA-KIT[1] [4–6], a general applicable multi criteria decision analysis (MCDA) framework, has been developed by this group in the context of framework, that has been nuclear emergency management (Fig. 1). Originally created for JRODOS, the MCDA-KIT applies MCDA to support decision making in emergency and preparedness, especially if the process is not distinct as measurements and simulation are

[1] https://portal.iket.kit.edu/projects/MCDA/

always affected by uncertainty. On top of that, as in such situations decision-making is in general also supervised by an advisory body, people with different backgrounds and expertise are involved in the process, causing different opinions to collide. Finding a *robust* and acceptable consensus for everyone involved is a difficult task. In this context, MCDA as a supporting method has become increasingly popular. The MCDA-KIT has successfully been applied and enhanced in many European projects [4–6], qualifying the group as advisory for IAEA. Moreover, further collaborations were established, e.g. with the group "Sustainable Bioeconomy" at the Institute for Technology Assessment and Systems Analysis at KIT developing an over-institutional tool, where the main objective is to create a framework for integrated sustainability and resilience assessment.

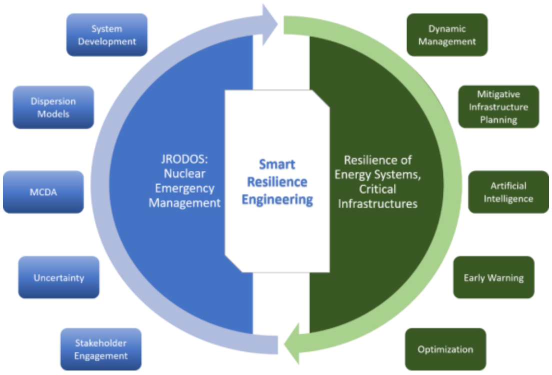


Figure 1 Research in Smart Resilience Engineering develops new methodologies benefiting from long-standing expertise in nuclear emergency management, while in turn adapting modern concepts of resilience engineering leads to innovations in JRODOS; some key competencies of these domains are highlighted in the surrounding boxes.

In conclusion, by combining design questions and management options, this group represents challenging research topics in resilience engineering that deal with different types of uncertainty – thereby, smart methodologies, models, and algorithms are developed, also applying artificial intelligence, in order to identify robust solutions be prepared for unexpected events, to mitigate adverse impacts through resilient designs of networked infrastructures, and to support decision making in effective crisis management (Fig.1).

Resilient Smart Grid Design and Microgrids

Basically, we believe that microgrids (MGs) contribute to a more resilient energy system in view of the aforementioned risks, see e.g. [7]. Applying criticality-based decision criteria for clustering MGs on the distribution level is a promising approach to link critical infrastructure protection to the energy system. Integrating this principle into network planning appears to be a feasible way forward in the context of energy system transformation, in which large investments are expected anyway [8]: this is not about extra measures to strengthen resilience, but about understanding certain topological degrees of freedom in design to increase urban resilience.

In this context, MGs can be seen as built-in redundancies giving rise to a cellular clustering of a distribution area: local resources are able to be self-sufficient in a small area for a certain period of time and furthermore MGs can switch to island mode if the overall grid fails to supply power [9]. How to design MG structures is not cast in stone as well [10–12].

Roughly speaking, the size of a MG depends on the power sources, storages that are installed, the power consumption profiles of the infrastructures/consumers in there, and the maximum expected duration of self-sufficient power provision. Thus, topological degrees of freedom appear in the design of power and smart metering infrastructures but as well in terms of cellular clustering of an energy system.

There are known graph-based network metrics that can be applied as weighted indicators in composite resilience metrics by making use of multi-criteria decision analysis (MCDA), where

Table I: A list of known graph-based network metrics see e.g. [13]

$\boldsymbol{l}$	characteristic path-length	Efficiency- average of the shortest path lengths
$\boldsymbol{c_b}$	central point dominance	Dominance of particular nodes
$\boldsymbol{f_c}$	critical ratio of defragmentation	Removal of a fraction $\geq f_c$ leads to a defragmentation of the network in different clusters – robustness of a network against catastrophic natural events (e.g. earthquake)
$\boldsymbol{\lambda_2}$	algebraic connectivity	Expresses the number of disjoint paths, i.e. the network remains fully connected despite the removal of nodes
$\boldsymbol{r_m}$	meshdness coefficient	Robustness and path redundancy – failure of nodes

the weights can be specified through an analytical hierarchical process (AHP) with the help of stakeholder engagement [13].

If we consider MG clustering, statistical peak load values and initial criticality of network nodes as further attributes of a distribution network, there is the following metric analogously defined as in [14]:

Let $\mathcal{M}$ be the set of all MGs in a smart grid (SG) and $\mathcal{I}_A$ be the index set of all infrastructures that lie in an MG $A \in \mathcal{M}$. Furthermore, we denote the statistical power peak demand of a consumer $i \in \mathcal{I}$ with d_i. A measure for criticality-demand concentration is given by

$$CD_A^{x,y} := \sum_{j \in \mathcal{I}_A} \left(\frac{c_j}{\sum_{k \in \mathcal{I}} c_k} \right)^{1-x} * \left(\frac{d_j}{\sum_{k \in \mathcal{I}} d_k} \right)^{1-y} \quad (1)$$

where $0 \leq x, y \leq 1$ and $x + y = 1$. Depending on the values of x and y, the greater this indicator is the more critical and tense the supply of infrastructures in A and the provision with critical services might get in times of disturbed power supply. The new metric associated to a SG is given as

$$CD := \max_{A \in \mathcal{M}} CD_A \ , \quad (2)$$

where x and y where omitted for better readability.

Hence, CD can be integrated into an MCDA-based resilience metric as described above for urban resilience assessments of smart distribution grids. It is important to point out, that the list of metrics given here does not refer to power physical constraints, however they play a crucial role from a network perspective. Nevertheless, power physical constraints or metrics should be considered to better assess the feasibility of power system designs – this is subject to current research. Furthermore, this approach can be adapted to any other networked infrastructure including hydrogen supply systems.

Resilient Energy Management

The IEEE standard 1366 [15] specifies a series of twelve reliability indices for power distribution systems, the most familiar of which are SAIDI (System Average Interruption Duration

Index) and SAIFI (System Average Interruption Frequency Index). Roughly spoken, SAIDI and SAIFI refer to periods without power supply and are useful in a posteriori assessments of the reliability of power distribution systems. LOLE (Loss of Load Expectation) refers to the number of hours per year during which supply is statistically expected not to meet demand in the long run. Since these indices are determined statistically, they are not subtle enough for the objective of having fine resolved measurements of security of supply as a basis for short-term or real-time decision-making.

The purpose of this subsection is to propose a (global) criticality-based metric that might be used in some sort of composite resilience metrics also taking efficiency and fairness into account [16].

We assume that infrastructures are equipped with smart meter, which are able to prevent power consumption above a specific threshold and furthermore have a certain power demand flexibility that depends on their sub-processes and the current demand of the infrastructure's functions. If $I := \{1, \dots, N\}$ is the set of all infrastructures from an urban distribution network, then we express the demand flexibility of an infrastructure $l \in I$ with the interval $\left[P^l_{D,min}, P^l_{D,max}\right]$ and its global criticality with c_l. Of course, there are infrastructures that need to maintain all sub-processes in order to fulfill their main tasks sufficiently, e.g. in dialysis clinics, dialysis machines, pumps, hot water disinfection systems etc. have to be in operation mode concurrently.

Let us consider k intervals of fixed length, e.g. 30 minutes, and let $\mathfrak{sp}_{l,t}$ be the assigned power to infrastructure l in time interval t, which is considered as the power threshold l cannot exceed. We define the following urban resilience indicator for power distribution:

$$\mathfrak{si} := \sum_{t=1}^{k} \sum_{l=1}^{N} \widetilde{c_l} * Q_{l,t} \,, \tag{3}$$

where – assuming there is at least one $i \in \{1, \dots, N\}$ with $c_i \neq 0$ such that $\widetilde{c_l} := \frac{c_l}{\sum_{j=1}^{N} c_j}$ is well-defined – $\widetilde{c_l}$ is called the normalised variant of c_l and

$$Q_{l,t} := \begin{cases} 0 \,, \mathfrak{sp}_{l,t} < P^l_{D,min} \\ \frac{\mathfrak{sp}_{l,t}}{P^l_{D,max}} \,, P^l_{D,min} \leq \mathfrak{sp}_{l,t} \leq P^l_{D,max} \\ 1, P^l_{D,max} < \mathfrak{sp}_{l,t} \end{cases} \tag{4}$$

characterizes the quality of power supply from the customer's perspective. In [16] first simulation results were presented, which have shown that instead of having controlled load shedding as described in Fig. 3, operationalizing this type of indicator in SGs can result in urban resilient – fair and efficient – power flows avoiding large-scale blackouts and in a significantly improved $\mathfrak{si}$, see Fig. 2.

Instead of having a controlled load shedding as described in Fig. 3, where large areas were switched off in a round-robin manner, smarter distribution could avoid such blackouts and assign power thresholds in an urban resilient and physically feasible way to the customers – i.e. no large-scale blackouts would occur, see Fig. 2.

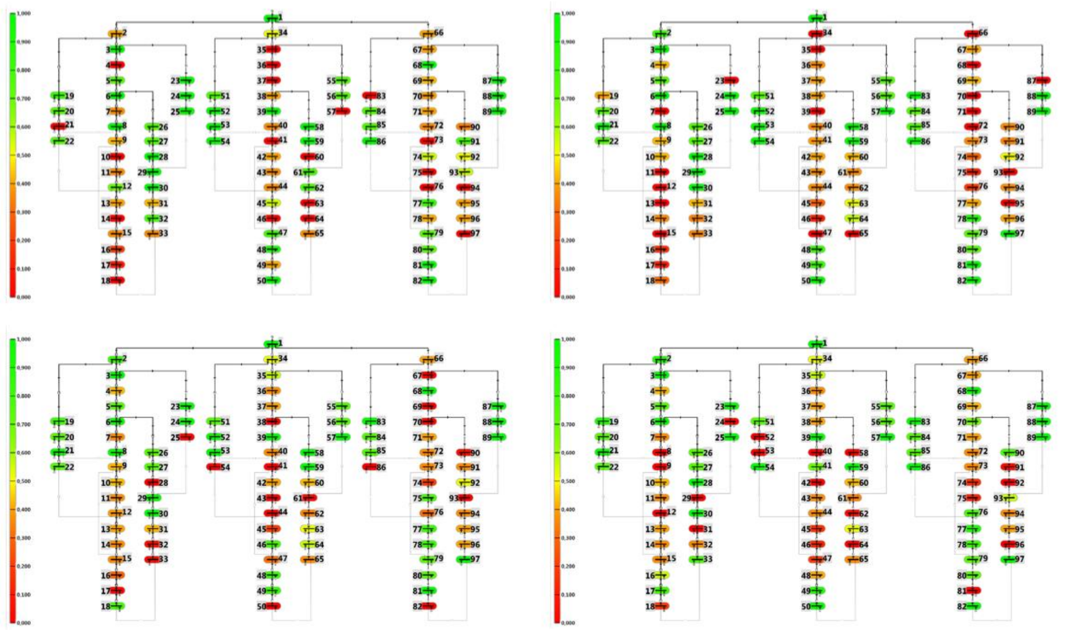
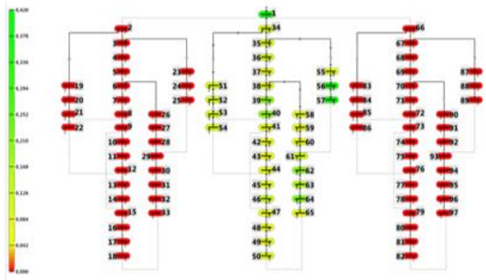


Figure 2 Heat map of the relative power supplies: in contrast to the rolling blackout of Fig. 3 continuous power flows are realised in an urban resilient, fair and efficient way over four time steps (red colour indicates induced blackout) [16]

	Referring to time slots of length 30, 90 minutes ...									
	1	2	3	4	5	6	7	8	9	...
A	●			●			●			
B		●			●			●		
C			●			●			●	



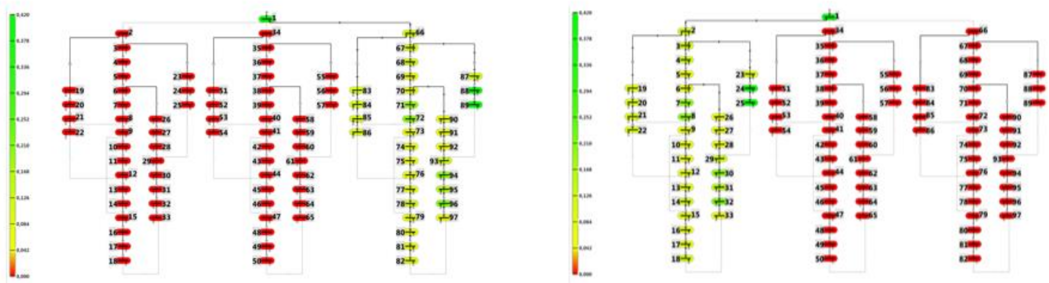


Figure 3 Three supply areas alternately taken off the grid in a round-robin manner – red colour indicates induced blackout [16]

Dynamic Measure Development – Agent-based optimization

Well-known features of agent-based modelling include scalability and simple adaptability of specific agent models and parameters. Besides a flexible integration of new agents, also further *preferences* can be included on an agent-specific level and calibrated or dynamically weighted depending on the agent's environment and forecasts w.r.t. various aspects related to the demands and resource availability e.g. weather forecasts in conjunction with renewable energy generation. Furthermore, based on the various needs of agents, representing different stakeholders or entities in a system, their preferences, and *global strategic goals,* solutions on how to distribute resources in a resilient way can be decided by negotiation- or optimization procedures targeting at identifying feasible and robust measures, and simulated. Agents' preferences and global strategic goals are considered as a result of a two-stage MCDA-process, which might be influenced by boundary conditions or sudden state changes.

Therefore, a resource independent agent-based optimization framework (ABO-F) has been set up that distinguishes between three different agent types: networked-, non-networked-, and purely demanding agents. Once this ABO-F has been instantiated according to a specific context, we speak of a multi-agent system (MAS). This MAS is equipped with a certain resource taxonomy that defines a universal language, which allows agents to communicate particular resource needs as well as offers. First simulation and optimization results were produced in the context of pharmacies (further agent models are to be included [17]) and urban crisis management, see Fig. 4 – as ABO-F is considered as an engine for smart crisis management it is improved and extended continuously, where a particular focus lies on optimization and artificial intelligence. It is envisaged that ABO-F will be integrated into JRODOS.

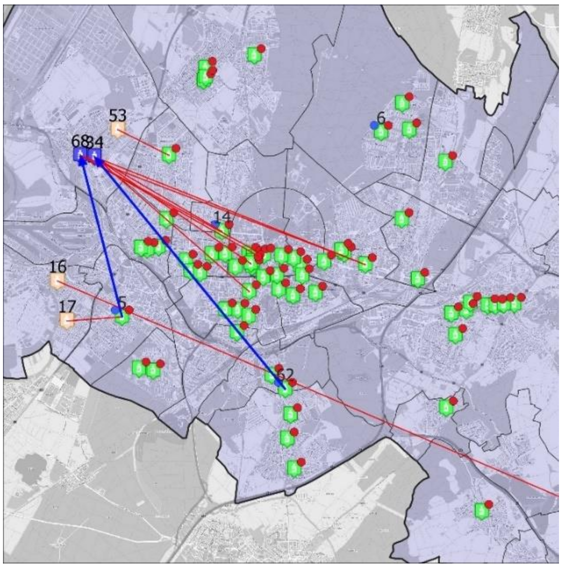


Figure 4 Pharmacies lacking power and medicine have blue icons, pharmacies lacking only medicine have yellow icons. All pharmacies offering medicine or an emergency power unit (EPU) have a red or blue dot resp. The edges describe a possible solution of allocating medicine and EPU.

Nuclear Preparedness and Response

Nuclear preparedness and response remain an important research topic due to research needs identified at the international level within the NERIS[2] (European Platform on preparedness for nuclear and radiological emergency response and recovery) SRA (Strategic Research Agenda) and at the national level with the many Nuclear Power Plants surrounding Germany[3]. To support decision making KIT has coordinated and is coordinating all research activities related to the decision support system JRODOS[4] (JAVA based Real-time Decision Support). The system is able to support decisions about the introduction of a wide range of potentially useful countermeasures

[2] https://eu-neris.net/library/sra.html

[3] https://www.bmu.de/en/topics/nuclear-safety-radiological-protection/nuclear-safety/response-to-fukushima/overview/

[4] https://resy5.iket.kit.edu/JRODOS/

(e.g., sheltering and evacuation of people, distribution of iodine tablets, food restrictions, agricultural countermeasures, relocation, decontamination, restoration, etc.) mitigating the consequences of an accident with respect to health, the environment, and the economy. It can be applied to accidental releases into the atmosphere and into various aquatic environments. Appropriate interfaces exist with local and national radiological monitoring data, meteorological measurements and forecasts, and for adaptation to local, regional and national conditions worldwide.

Nuclear emergencies, as demonstrated with the Chernobyl and Fukushima disasters, do not stop at national borders. However, so far, no harmonized response was established in Europe or worldwide. To overcome this constraint, The European Commission supports the installation of JRODOS in national emergency centres. Having one system operational, at least results are comparable, even if national regulations may differ.

KIT has installed JRODOS in many countries, e.g. starting in 2020 in 6 West-Balkan countries, 6 countries of the Gulf Cooperation Council, Armenia and Iran.

Ongoing research to improve JRODOS is related to source term reconstruction [29] and ensemble modeling to capture uncertainties in the early phase of an emergency [27, 28].

Ensemble Modelling and Uncertainty

The potential source term as well as meteorological forecasts are the main uncertainties in the early phase when the release to the atmosphere is expected or ongoing [26]. On the other hand, evacuation of the population is most effective before the release has started. To investigate these uncertainties, research was conducted within CONFIDENCE[5] and JRODOS has been expanded with ensemble modelling functionalities [28]. One of the questions

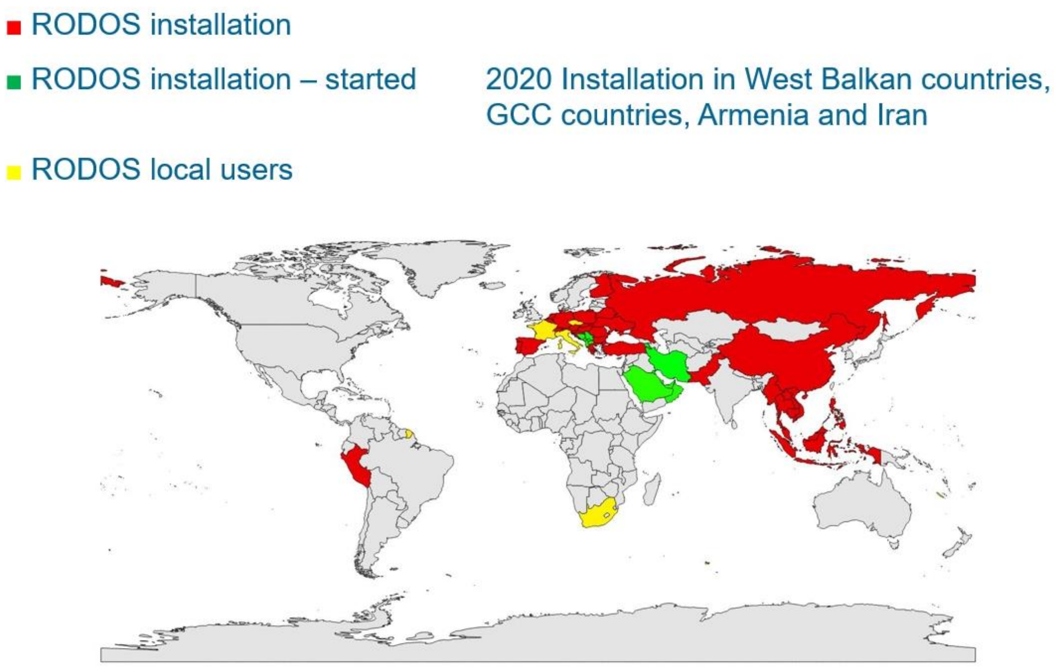


Figure 5 JRODOS installations worldwide.

[5] https://portal.iket.kit.edu/CONFIDENCE/index.php

that was raised but not answered was "do ensembles capture the full uncertainty of a meteorological forecast?".

To look into this question, KIT collected ensembles from three different weather providers

- NOMADS[6] with 20 ensembles
- Canadian[7] weather service with 21 ensembles
- German[8] weather service with 41 ensembles

at distinct times in March 2020. Sites all over the world were selected and ensemble calculations have been performed. To investigate only the meteorological uncertainties, the source term was fixed. The results are presented as percentiles, exceeding a particular dose value. Dark colors mean that many ensemble members fit therein, whereas lighter colors show areas where only some ensemble members predict exceedance of the threshold. The following figures show example results for a more constant meteorological situation and for one with changing wind directions.

Even if preliminary, these two examples indicate that using one provider does not capture the full uncertainty that exist when considering other weather providers. Fig. 7 shows very similar results from all three weather providers; however, the meteorological conditions were quite stable. Fig. 6 on the other hand demonstrates that all three providers differ considerably, at least for the lower percentiles. Nevertheless, Fig. 6 also demonstrates the added value of an ensemble assessment compared to a single forecast. As ensemble modelling is very time consuming – each ensemble member run is one project in JRODOS – a further research question for the following years is the number of ensemble members that is sufficient for operational use, considering the time constraints but reflecting still the existing uncertainty band.

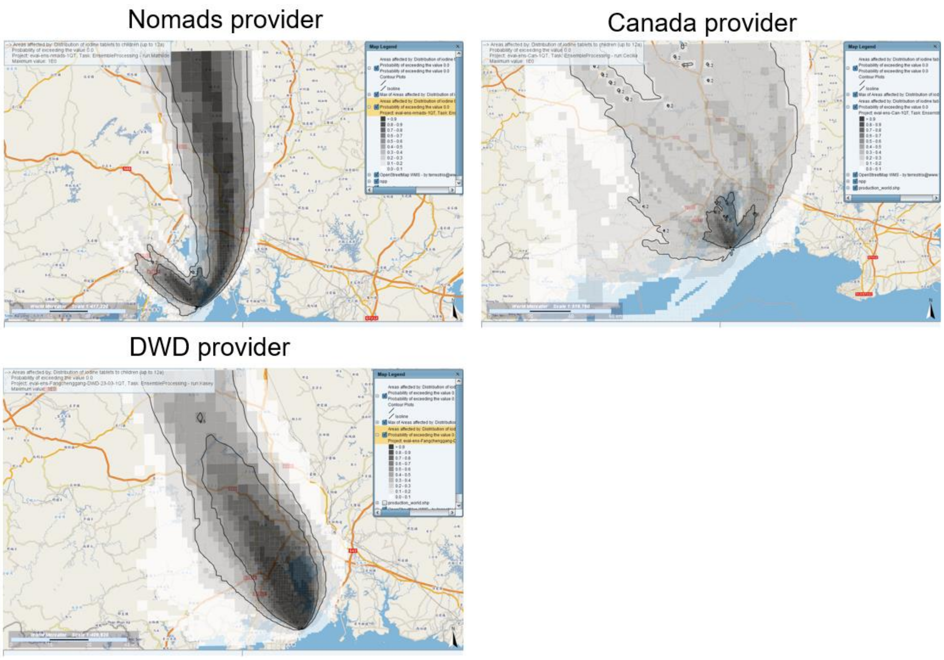


Figure 6 Release in China, exceedance of iodine prophylaxis for children (50 mSv).

[6] https://nomads.ncep.noaa.gov/
[7] https://weather.gc.ca/canada_e.html
[8] https://www.dwd.de/EN/Home/home_node.html

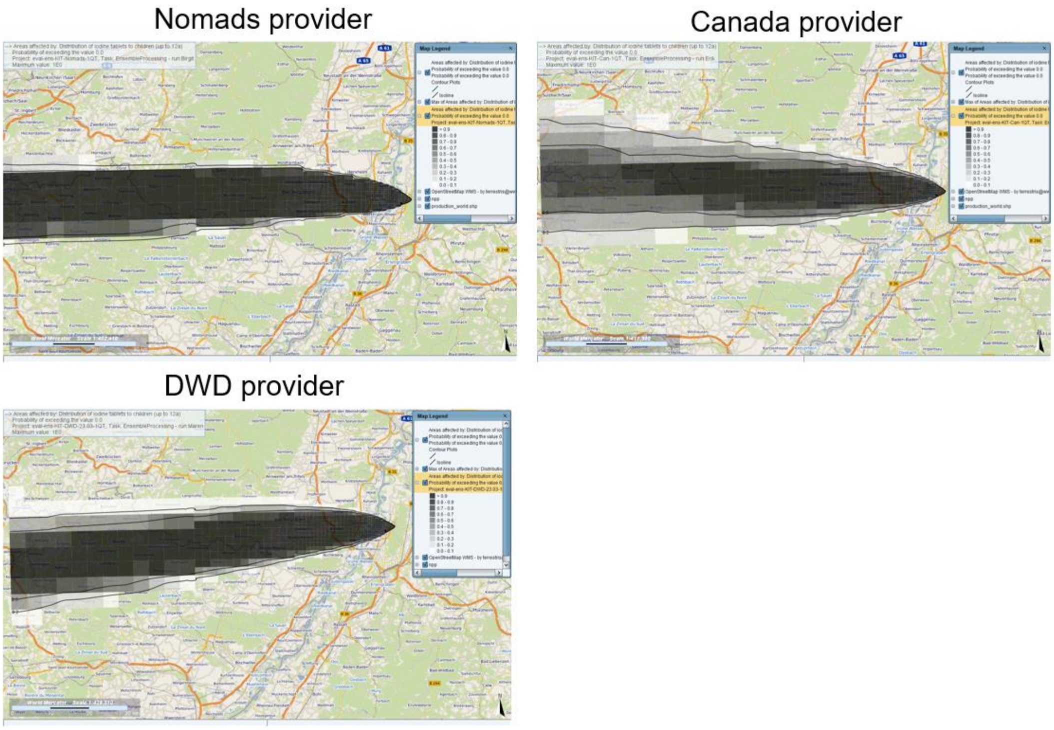


Figure 7 Release in Germany, exceedance of iodine prophylaxis for children (50 mSv).

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