A Modeling Framework to Support Resilient Evolution Planning of Smart Grids

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Abstract. Cyber security is becoming more and more relevant with the advent of large-scale systems made of independent and autonomous constituent systems that interoperate to achieve complex goals. To ensure security of cyber-physical systems, it is important to analyze identified threats and their possible consequences. In case of smart grids as an example of a complex system, threats can result in power outages that damage the continuous supply of energy that is required from critical infrastructures. Therefore, city planners must take into account security requirements when organizing the power grid, including demand-side management techniques able to mitigate the adverse effects of outages, ultimately improving grid resilience. This paper presents a modeling framework developed within the IRENE project that brings together methodologies, policies and a toolset to evaluate and measure the resilience of the targeted smart grid. This will support stakeholders and city planners in their activities, specifically the resilient evolution planning of Smart Grids.

Keywords: Threat analysis · Smart grids · Evolution · Resilience · City Planning · Power flow equations · Demand side management · IRENE

1 Planning for Resilience

This paper describes the modelling framework that was developed within the IRENE project [18]. This framework aggregates methodologies, policies and the toolset to evaluate the resilience of the targeted smart grid. The framework will be used to investigate threats in the smart grid and to implement the identified solutions. Based on the smart grid topology, possible outages and risk analyses, the framework provides a way to support city planners in their decisions. The usage of the modeling framework is then regulated by [19], which traces the bounds of the interaction among different users e.g., generic stakeholders, DNOs, city planners, regulators.

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The framework includes tools performing an extensive threat analysis that leads to the identification of possible root causes of outages (kill chains, [13]), which are then simulated to estimate the capabilities of the grid to supply its components also when an outage happens. Further, different mitigation methods are integrated into the framework to enable users to evaluate the efficiency of fault and attack mitigation measures, the energy resilience outcomes, and the impact on critical infrastructures.

More in detail, this paper summarizes all the tools developed within the IRENE project [18] and devises a strategy and a workflow to integrate them in a unique framework. This gives a final output that summarizes the results of the single tools, ultimately providing resilience metrics of the investigated smart grid that are built taking into account all the technical contributions of IRENE. The document focuses on: (i) the integration of disconnected tools within the IRENE modeling framework by providing a workflow for the consequent usage of such tools, and (ii) the validation of such integration, using a case study in which we executed the tools according to the workflow above.

The document is structured as follows. Section 2 summarizes all the inputs of the modeling framework, while Sect. 3 defines the tools that were developed within the project. For each tool, we report a description of its functioning and its interfaces. In Sect. 4, we define the workflow that integrates all the single tools supporting the open modeling framework, which is finally executed in Sect. 5 by applying the workflow on a simple smart grid scenario based on the IEEE 14 node grid topology.

2 Inputs of the Modeling Framework

In this section, we report the main inputs that the user must provide to exercise the modeling framework. More in detail, this inputs are needed for the execution of the tools constituting the toolset that, together with the workflow (see Sect. 4) and some policies, defines the framework mentioned above.

Portfolio of Grid Changes (GC). In general, the IRENE project aims at investigating a specific (smart) grid scenario S. The grid scenario is mainly composed by a grid topology and assumptions about the city where the grid is installed. Scenarios can be updated based on long-term planning that relies on the knowledge of experienced city planners and other city-level stakeholders. At the same time, local and punctual intervention can be performed to improve the grid efficiency or to fix address some issues. Therefore, updates can be planned and implemented due to:

- Long-term planning of evolutions, defined by city planners in agreement with the relevant stakeholders. Municipalities may decide to invest money to make the energy distribution more resilient and efficient. Further, they may decide to modify governance e.g., opening the market to new DSOs, or promoting the *prosumers* (both producer and consumer) model;
- the inclusion of specific mitigation strategies to improve robustness and security in an existing part of the grid;

- the addition or removal of electric components to improve specific metrics related to the grid (e.g., a new direct power line between two buildings, new breaker, redundant hardware to improve fault tolerance).

List of Grid Components (CL). The list of components is based on the lists identified in [1, 2]. Moreover, novel components were identified in the process of the project, to guarantee a specific and realistic architectural description [4], supported by available datasets. The additional components consist mainly of commercial building types that allow a more realistic modelling of urban consumption. The characteristics of these buildings are described in [8].

Consumption Profiles (CP). According to the origin of the consumption data, we mainly distinguish between (i) *commercial* buildings, and (ii) *residential* buildings. Both the MGE and OGM tools (see Sect. 3) use the reference building models from the US Department of Energy (DoE). The dataset called "Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States" is found under [9]. Since several consumption modules such as cooling, heating, ventilation, ICT etc. are available, new critical and interruptible consumption profiles are created. Flexible loads are added according to the configuration and where possible e.g. cooling, their output is calibrated to fit the profile. The household profile, instead, is taken from the *Elexon Ltd.* database, representing a normal household profile (categorized as *Profile Class 1* in the UK, with 24 h of consumption data [10]. Moreover, an important feature of these profiles is the possibility to aggregate the profiles forecast, which is accomplished through the active-aware-based *Ensemble Kalman Filter* (EnKF), first introduced in [7].

Threat List (TL). The threat list and the attacker profiles are defined in [1, 2]: starting from the NIST [3] guidelines, we built the IRENE list of 38 threats related to cyber-security that is used to define the disaster scenarios [2]. Each threat belongs to a category that is used to classify them depending on their characteristics (e.g., attack conduction, gathering information, accidental and environmental).

Outage Scenarios (OS). The threats that can affect a given grid scenario can be mitigated applying the techniques as presented in [1]. Indeed, (i) such mitigations may not be able to completely prevent the occurrence of the threat or negate its effects, or (ii) the effectiveness and efficacy of the identified mitigations may require further investigation. In fact, at this point, the extent they are able to mitigate the adverse effects of a threat is not analyzed or known a priori.

Specifically focusing on outages, we consider having an *outage scenario*, or rather the consequences of the happening of a threat that negatively impact the grid resulting in one or more outages. The expected duration of this outage is related to the specific source threat and grid scenario we are dealing with. Outage scenarios must be defined by Risk Assessment (RA) experts once the grid scenario is defined. Outage scenarios constitute one of the main dimensions of analysis to evaluate the resilience of the smart grid in presence of such detrimental events.

3 Tools Constituting the Modeling Framework

This section reports the tools that were built within IRENE that, together with methodology and policies, constitute the modeling framework. These tools have been already described in [5, 12–14]. We report a summary here for completeness.

Evolutionary Threat Analysis (ETA Tool). The threat analysis process described in [1] led to the implementation of an evolutionary threat analysis tool. In fact, the threat identification and analysis framework has been implemented into an integrated tool determining the variation of mitigation strategies and the scenario-based distribution analysis [5]. It makes use of the *Colibri-Java FCA API*[1] to analyze the distribution of threats. The tool takes as input the evolution steps defined in terms of evolutionary features and the mapping between threats and their high-level mitigation strategies [1], aiming at providing an actual list of mitigations depending on the current grid scenario, that is obtained merging the evolution steps with the initial grid scenario.

The analysis is evolutionary, meaning that the actual list of threats CT and mitigations is obtained starting from the previous result and considering the new evolution step that e.g., is defined by city planner. Each evolution step is composed of a set of grid changes (e.g., adding/removing a specific component) that can make the set of threats (and consequently mitigations) bigger or smaller. The tool takes the partial set of mitigations and modifies it considering the introduced changes.

Interfaces. (i) ETA: S × GC × TL → CT.

BayesianFair Threat Evaluation (BF Tool). This tool allows numerical threat assessment based on the FAIR factors [12], namely Contact, Vulnerability, Action, and Control Strength. The numerical outputs given by *BayesianFAIR* can help to further rank threats in the same severity SE category (e.g. High or Very High), which is an extension of the FAIR framework [12]. This will be helpful to prioritize threats to assign the constraint security resources, especially in cases many threats are considered in the network [13]. In real scenarios, for each threat, we assume that security experts give input state for every factor. All the Bayesian parameters are obtained from the FAIR tables [16] as guided in the FAIR model and encoded to the tool. Although the parameters are fixed for this particular implementation, they can be updated manually if users want to assess based on different FAIR tables. The assessments of the tools are adjusted to always be in-line with the FAIR assessments.

Interfaces. (i) BF: CT × C × A × V × CS → SE.

Single Line Failure Simulation (SILFAST Tool). This tool considers a mid-voltage grid topology in which the buses and branches characteristics are known (given). The loads on the buses are also given and they correspond to entire microgrids or low-voltage radial grids that are considered in detail in the MGE tool below. SILFAST analyses the response of the grid to single line (branch) failure. Line failures are frequent consequences of threats that can be either natural disasters (e.g., fires, floods,

[1] https://code.google.com/archive/p/colibri-java.

earthquakes, storms) or cyber-attacks, which could lead to opening line circuit breakers. If a line is disconnected, the power distribution takes place via the remaining lines, and since the loads remains the same, an overload situation is created on some of these lines. If not handled by disconnecting loads or adding generation, the lines will trip after some time creating cascading failures and leading to blackout.

The mechanism to determine this overload is to calculate power flows on the topology created by removing one branch and reporting overloaded links.

Interfaces. (i) SILFAST: S × OS × OL → GS(A).

MicroGrid Evaluation (MGE Tool). *Demand Side Management* (DSM) in micro-grids with flexible loads, distributed generation (DG) and storage has been already addressed previously [6]. However, few works have studied the DSM effect on the microgrid operation during long lasting outages. Using the classification in [6], we focus on a secondary control centralized architecture, in which the time horizon is minutes up to hours, therefore - significantly larger than for primary control systems.

Briefly, the MG controller reads the latest flexibility and consumption plans from the CEMS and computes updated set points (six-hour profiles). In case the proposed load is too high, it sheds certain demands within their flexibility limits. The tool uses certain demand optimization architecture, algorithms and control exchange messages between the MG controller and the building controllers (CEMS). The runs under different configurations produce the energy schedule prior and during the outage. The local control actions for each CEMS are reported, as well as the efficiency of generation, storage and load shifting. A user interface shows the evolution of different house parameters and variables during the simulation. Specific metrics are computed to the energy management performance [14] in a particular grid scenario.

Interfaces. (i) MGE: CP × OS → GS(A) x OL.

Overall Grid Modeling (OGM Tool). A complete holistic approach of a supply, demand and load balancing optimization module is developed for grid distribution planning purposes. The optimization model allows the full integration of the demand forecast, wholesale electricity market price, distributed generators (renewable and non-renewable), energy storage systems, and the perturbation of outage events. The demand forecast and assimilation is performed using the active-aware-based *Ensemble Kalman filter* (EnKF). The outage event is included to evaluate the resilience index RI of the grid, or rather its capability in sustaining the outage by isolating from the main

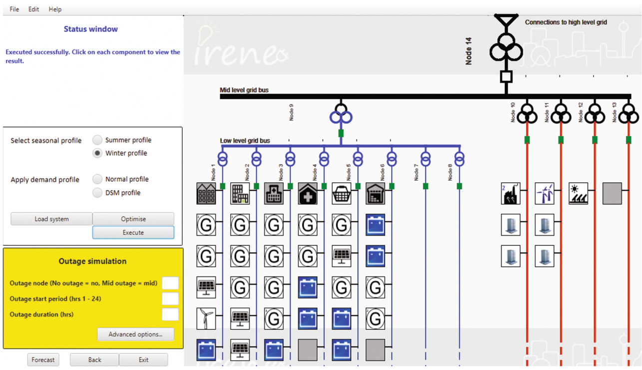

Fig. 1. Interface of the OGM tool

grid and operating in islanded mode, or by isolating grid portions and dropping the load (normal grid-connected operation for unaffected grid nodes). The ability of in sustaining the islanded operation generates a grid state GS, which can be normal GS(N) or anomalous GS(A), and allows the evaluation of the resilience of the urban grid.

The optimization module is performed using the *Matlab* software. The dual-simplex algorithm is applied for *the Linear Programming* (LP) problem of the microgrid optimization. Sensitivity analysis is also performed though the creation of different scenarios in order to evaluate the effectiveness of the grid optimization module. Then, the grid optimization model is implemented into a toolset in [11]. Such model is deployed into graphical user interface (see Fig. 1) using Java environment to allow users to manipulate and control the simulation of the toolset as developed based on the grid optimization model.

Interfaces. (i) OGM: S $\times$ CP $\rightarrow$ GS(N) (No RI without outage), (ii) OGM: S $\times$ CP $\times$ OS $\rightarrow$ GS(A), RI, (iii) OGM: S $\times$ CP $\times$ OS $\rightarrow$ GS(N), RI.

4 Workflow

We proceed with the description of the *workflow*, or rather the flow of information and actions that the user of the framework can follow to fully take advantage of the IRENE modeling framework. Since the diagram in Fig. 2 is quite complex, we painted with different colors the different phases of the flow. Starting from the upper left corner of the figure, the current grid scenario *s* is initialized with the grid scenario *is* given as input. Then, the process can start.

(Orange Blocks). We analyze the current grid scenario *s* looking for all the threats that can be identified using the *ETA* tool. This provides a set CT of current threats that is composed by local threats (LT), which can be mitigated taking actions affecting the single components, and outage threats OT, that instead can directly lead to outages and cannot simply be mitigated locally. The current threats are next estimated using the *BayesianFAIR* (BF) tool, which applies a probabilistic method to estimate a severity *se* of each threat depending on some inputs that are provided by RA experts. This produces a severity set SES that can be used to link each current threat with its estimated severity. All the LT threats can be mitigated according to the links between threats and mitigations summarized in [1]. Moreover, the availability of SES can help city planners to choose which threats have to be mitigated earlier. Once LTs are mitigated, the planner can choose to analyze the grid more in detail, looking at how the grid reacts when one of the OT actually generates an outage.

(Yellow Blocks). In particular, using the set of all the possible outage scenarios OSS we can map each OT to one or more outage scenario COS the current threat can generate e.g., a *Denial of Service* attack targeting a critical node of the grid can block the energy supply. For each of these outage scenarios *cos* we run the MGE and the OGM tools to evaluate the ability of the grid to react to these detrimental events.

(Green Blocks). The green steps in Fig. 2 deal with the evaluation of the response mitigation to an outage. The path to be followed in Fig. 2 depends on the outage type

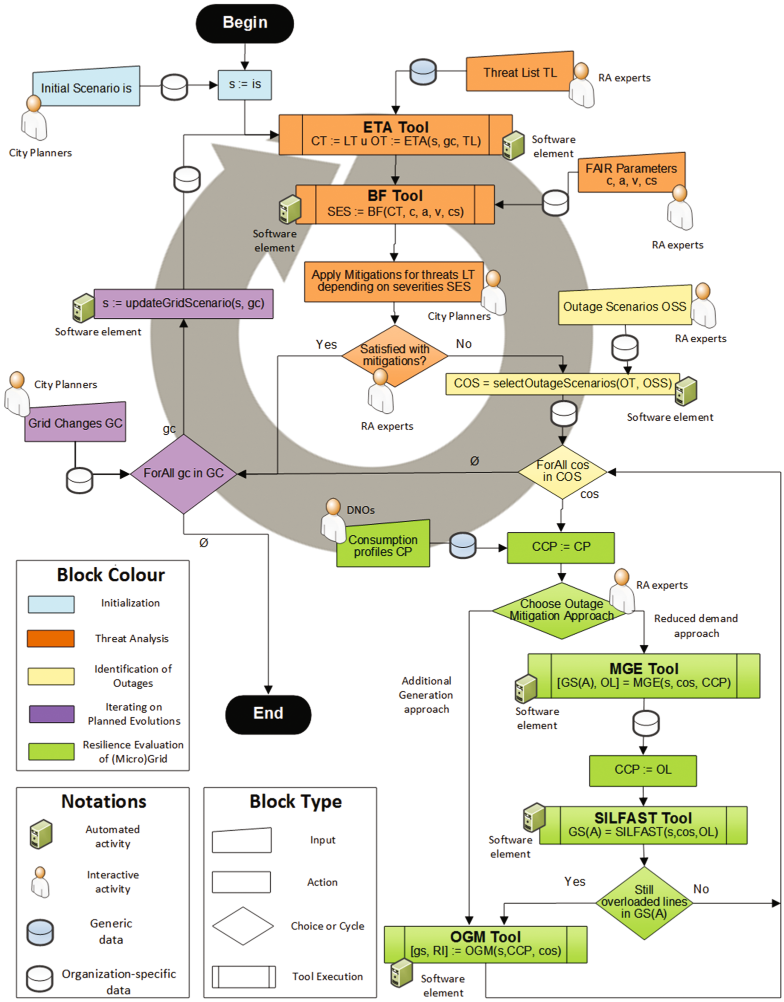

Fig. 2. The workflow constituting the IRENE modeling framework. (Color figure online)

and on the availability of techniques allowing demand side management. The choice is left to the RA expert, who knows the actual techniques installed in the grid and can decide for one path or another. Overall, the usage of reduced demand is preferable since it does not charge additional costs, which are instead required if the RA expert chooses to go for the additional generation path.

(Purple Blocks). Once all the outage scenarios related to *s* are investigated, we check if some grid changes are provided by the city planner. If he predicts several evolutions for its grid, he builds a non-empty GC set, that triggers a new analysis of the threats and the energy provision considering each grid change *gc* in GC (see purple boxes in Fig. 2). If GC is empty, or after examining all the changes in the set, the workflow ends. The result is a grid scenario after considering all the grid changes and in which all the mechanisms to mitigate the identified threats are implemented, guaranteeing energy provision to all the components of the grid according to their requirements also in presence of some outage scenarios due to the manifestation of some threats.

5 Exercising the Framework

In this section, we simulate a sample usage of the open modeling framework we described in the paper. More in detail, we provide the evaluation of a sample grid scenario using the tools according to the workflow described in Sect. 4.

Reference Topology. Within IRENE [4] it has been decided to use a known test grid network, the IEEE 14 node grid [17]. Each node represents a different micro-grid. To instantiate a case study, we built the generations and the load distributions of each of the micro-grids involved in the IEEE 14 node grid. Moreover, since the original grid capacity is 230 MW, we scaled it down and populated the microgrids. We assume that the nominal voltage of each bus is 2 kV i.e., a secondary station transformer 2/0.4 kV. Moreover, we assume that (i) the city has an important strategic relevance and is consequently exposed to terrorism, and (ii) the city is in a seismic zone.

Scenario. A node in the IEEE 14 node grid (see [17]) is generally modelled as a whole microgrid associated to an urban neighborhood. For instance, we focused on the total load of Node 3, which is 940 kW and indicates a microgrid constituted by the following components (see [1] for the IRENE grid component list): 1 charging station (with parking lot for 12 EVs), 17 smart houses, 8 small offices, 10 apartment blocks, 1 supermarket, and 1 energy storage i.e., a battery with fixed capacity.

Outage Scenario. After a preliminary analysis using the ETA tool on the grid scenario, we observed that a threat due to possible earthquake (i.e., IRENE threat 33 [1]) damaging Node 3 of the grid i.e., the "Energy storage" component, can cause a 6-hour outage. To clarify the validation process, we will consider this threat as responsible for an outage scenario that is used in the open modeling framework.

Exercising the Framework. We report an overview of the application of the workflow on the specified scenario. The complete description of this evaluation process can be found in [15]. According to the workflow, the first part of the process aims at estimating the exposition to threats of the grid scenario. Overall, the sample grid is exposed to 251 possible threats, roughly 69% structural and 31% that emerge from the interconnections and the relations among different components. In particular, we can observe how the IRENE threat 20 "*Conduct cyber-physical attacks on organizational facilities*" and the IRENE threat 31 "*Incorrect Privilege Settings*" emerge in the higher number of cases in this scenario. For example, cyber-physical attacks can be conducted from a smart home to the offices through the data line that is used by employees to log on organizational services using unsafe connections.

Nevertheless, the grid is in a seismic zone. Consequently, the likelihood of an earthquake is *High*. In this case, the first input state of the FAIR factor (C) is *High* and is the same for all rows in the grid components. However, the remaining input states are different for grid components, depending on the structure and the resistance of the grid components to the disaster. Results show that the Outpatient Clinic has the highest SE due to *High* probability of large-scale damages (i.e., power failure of the lines connected to Outpatient clinic), and the *Low* resistance to the damages (i.e., anti-seismic structure but no installation of backup-generations).

Considering the outage scenario due to the earthquake, power stations and line cables would be destroyed. The MGE tool would use demand management and determine the reduced total load of each microgrid during the outage. With this input data, we can apply the SILFAST test. We perform two series of experiments: one that uses regular loads, and one that take advantage of the output of the MGE tool. Considering the IEEE 14 grid topology, we obtain that using the regular loads roughly half of line failures produce multiple line overloads, ultimately leading to blackout. This adverse effect is mitigated considering reduced loads. In fact, with this loads blackouts can happen only with the failure of two lines: 1–2 and 4–9.

Then, we execute the OGM tool. Due to the earthquake, the microgrid is disconnected from the main grid. Therefore, the islanding mode operates within the microgrid level optimizing the dispatching of generating units. When the outage is solved, the islanding mode is stopped and instantaneous main grid re-connection is achieved activating the normal load. In this case, the specifications and installations of DGs, storage and renewables in the IEEE-14 node grid are adequate in responding to the complete outage. Marginal cost savings are achieved (£66.54) through the optimized generation dispatches, even though the usage of generation units is more expansive in order to balance the demand during the outage. The resilience index RI is based on the demand served during the outage [4] and computed as 1.0. The highest RI is expected due to the complete outage mitigation in this case.

From a decision making perspective, results about threat amount, mitigations, cost savings and resilience may help the city planner to understand economic and security implications of possible evolutions of the targeted power grid. For example, if a city needs a new hospital, the city planner may want to place it in the best location and with the more convenient connections with other buildings. Selecting parallel evolutionary steps where the hospital is placed in different areas of the existing topology can highlight the choice that has a better tradeoff between resilience, cost savings and security.

6 Concluding Remarks

In this paper, we described the modelling framework that was developed within the IRENE project [18]. This framework aggregates methodologies, policies and the toolset to evaluate the resilience of the targeted smart grid. The workflow implementing the methodology defined in the framework was applied to a case-study scenario based on the IEEE 14 node topology. This allowed to demonstrate the effectiveness of the framework and to show some preliminary results.

We highlight that most of the components constituting the framework are tailored for microgrids rather than generic high-voltage or mid-voltage grids. As a future work, these components can be expanded to be suitable also at a non-microgrid level.

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