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Abstract

The exploitation of any energy resource produces impacts and intrinsically bears risks. It implies that to make sound decisions about future energy policies, it is important to clearly understand the potential environmental impacts and risks in the full life-cycle of a project, distinguishing between the specific impacts intrinsically related to exploiting a given energy resource and those shared with the exploitation of other energy resources.

A wide range of possible environmental impacts can be associated with the shale gas development. In this report we arbitrarily divide these environmental impacts in two general groups: (1) impacts caused by ordinary routine operations, and (2) impacts caused by incidents due to system failures or extreme events. A close examination of these two impact groups can provide insights about the potential environmental impacts associated with exploiting unconventional gas resources. However, the impacts caused by incidents, being low probability/high consequence events, are those of paramount importance for the multi-risk assessment because such a kind of events have the potentiality of causing the most disastrous and unexpected damages.

The main objective of this report is the identification of plausible scenarios of events or chains of events related with shale gas development that may have an impact on the environment and/or the society. The multi-hazard/multi risk approach for this problem is set by considering multiple hazards (and their possible interactions) as possible sources of system's perturbation that might drive to the development of an incidental event. Given the complexity of the problem, we adopt a multi-level approach: first, perform a qualitative analysis oriented to the identification of a wide range of possible scenarios; this process is based on a review of potential impacts in different risk receptors reported in literature, which is condensed in a number of causal diagrams created for different phases/stages of a shale gas development project. Second, the most important scenarios for quantitative multi-risk analyses are selected for further quantification. This selection is based on the identification of major risks, i.e., those related with the occurrence of low probability/high impact extreme events.

The general framework for the quantitative multi-risk analysis is represented using a so-called bow-tie structure. It is composed of a fault tree on the left hand side of the graphic plot, identifying the possible events causing the critical (or top) event, and an event tree on the right-hand side showing the possible consequences of the critical event. Given the different categories of risk receptors considered, the following criteria have been used for structuring scenarios: (1) Impacts in primary risk receptors have been chosen as critical top events for constructing fault trees. These have to be well specified events (e.g., what and where it happens?); An example of a top event is “pollution of groundwater due to in-site leakage of fluids”; (2) identification of the boundary conditions with respect to external stresses. In practice, we define the type of external hazards that are going to be included in the analysis; (3) for each critical top event identified, a deductive technique is used to identify the possible causes of such failure, considering the boundary conditions defined and the level of resolution of the analyses; and (4) the identified top events are also the starting points of consequence analysis, which is evaluated for considering the impacts on a final risk receptors of interest. The later analyses will be structured using an event tree approach.

Keywords:

Multi-risk; risk pathway scenarios; shale gas development
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1. Introduction

Without exception, the exploitation of any energy resource produces impacts and intrinsically bears risks. Therefore, to make sound decisions about future energy policies, it is important to clearly understand the potential environmental impacts and risks in the full life-cycle of a project, distinguishing between the specific impacts intrinsically related to exploiting a given energy resource and those shared with the exploitation of other energy resources.

Technological advances as directional drilling and hydraulic fracturing have led to a rapid expansion of the development of unconventional natural gas (UNG) resources and, as a consequence, it is feasible that UNG development projects can get closer to inhabited areas raising both public health and environmental concerns (e.g., Broomfield 2012; COGCC 2009).

Hydraulic fracturing is a method used to stimulate or improve fluid flow from rocks in the subsurface. Traditional reservoirs have hydrocarbons (oil and gas) located in well-connected pores in the rock, whose permeability is often sufficient to allow extraction. In unconventional reservoirs (as e.g., shales), the natural gas is found in small and poorly connected pores and cracks and, for this reason, it is necessary to increase permeability by artificial means to extract this resource (e.g., Healy 2012). However, injecting large volumes of fluid into the subsurface is not an activity without risk. Consequently, it is suspected that the development of UNG can have links to a range of potential local environmental problems as, for example, slip on nearby faults, pollution of surface and ground water, and emission of volatile components.

The use of hydraulic fracturing has been the focus of much controversy. In fact, while a number of authors argue that the existing evidences supporting the negative environmental impacts of UNG development are overwhelming, other authors point out that the most significant environmental risks associated with such developments are similar to those associated with conventional onshore gas, including gas migration and ground water pollution due to faulty well construction, blowouts, and surface spills of waste water and chemicals used during drilling (e.g. Zoback et al., 2010). The fact that different actors with different perspectives and expertise play a role around the UNG development, it makes of this debate an interesting topic in which science is called to support the risk management process, providing objective inputs to share light over a number of critical issues.

As with any other energy resource exploitation, a wide range of possible environmental impacts can be associated with the shale gas development. Arbitrarily, we can divide these environmental impacts in two general groups: (1) impacts caused by ordinary routine operations, and (2) impacts caused by incidents due to system failures or extreme events. A close examination of these two impact groups can provide insights about the potential environmental impacts associated with exploiting unconventional gas resources. However, from the perspective of risk assessment, the impacts caused by incidents, being low probability/high consequence events, are usually those of paramount importance because such a kind of events have often the potentiality of causing the most disastrous and unexpected damages. Conversely, the impacts associated with routine operations are usually better constrained and managing such impacts is a relatively easier task.

The main objective of this deliverable is the identification of plausible scenarios of events or chains of events in which the activities related with shale gas development might have an impact on the environment. This activity is the first step before moving to the successive phase in which a methodological approach for quantitatively assessing the most specific scenarios is going to be developed. Before moving to the process of scenario identification, we present a brief description of the general framework for the multi-risk assessment.

The deliverable is organized as follows: first, a general overview of the main concepts related with the multi risk assessment problem are presented. In this section, in particular, a description of
possible strategies and methods for exhaustively exploring and structuring scenarios are discussed. Given that the analysis of environmental impacts includes all the phases of a project development, in the second section we briefly summarize the stages in a project development that are relevant for the identification of risk pathway scenarios. Once the conceptual framework has been set, in the last section we present the main risk pathway scenarios that have been identified, discussing briefly those that will be more relevant in the forthcoming phases of the SHEER project for quantitative analyses.
2 Multi-hazard/multi-risk assessment: Basic concepts

The main purpose of the multi-risk assessment is to harmonize both the methodologies employed and the results obtained for different risk sources, taking into account possible risk interactions (e.g., Marzocchi et al. 2012, Garcia-Aristizabal et al. 2015, Liu et al., 2015). The types of events considered in a multi-risk analysis may include events threatening the same elements at risk without chronological coincidence, or events occurring at the same time or shortly following each other, because they are dependent on one another or because they are caused by the same triggering event (European Commission 2010). The first case represents what is generally denominated ‘multi-hazard risk’, whereas the second case represents the possible interactions or cascading effects that are one of the main characteristic elements of multi-risk assessment (for details see, e.g., Marzocchi et al., 2012; Gasparini and Garcia-Aristizabal 2014; Liu et al., 2015).

The multi-hazard assessment may be understood as the process to determine the probability of occurrence of different hazards either occurring independently or by a triggering process (cascading effect). In general terms, one can split the multi-hazard concept into two possible lines of applications, where multi-hazard assessment may be seen as (1) the process of assessing different (independent) hazards threatening a common set of exposed elements and (2) a means of identifying and assessing possible interactions and/or cascade effects among the different possible hazardous events (for details see, e.g., Marzocchi et al., 2012; Gasparini and Garcia-Aristizabal 2014; Liu et al., 2015).

Considering the assessment of different, independent hazards, the main effort within this multi-hazard perspective is the harmonization of the hazard assessment for the different threats. This is generally considered a requirement in multi-risk analysis to make the risks posed by different threats comparable (e.g., van Westen et al. 2002; Marzocchi et al. 2012, Garcia-Aristizabal et al. 2015). Conversely, a multi-hazard assessment considering interaction/triggering effects is, in general, a more demanding process and the most pertinent typology of problem to be approached regarding the application of multi-risk assessments to shale gas operations.

2.1 Interactions, triggering and cascading effects

The occurrence of one event has the potential of changing the probability of occurrence of another event, leading to potential cascades (Liu et al., 2015). The typology of interactions that can be grouped under this name are in fact phenomena in which the physical process of interest is a pure triggering mechanism in which an initial event produces a perturbation that, when acting on a given system, may bring it to an unstable state, forcing it to find a new equilibrium state that matches the changing framework conditions. Reaching this new equilibrium may imply the occurrence of an event that, in this case, may be said to be triggered by the initial one (Gasparini and Garcia-Aristizabal 2014). The link between the intensity of the triggering event (e.g., the ground shaking caused by an earthquake) and the intensity of the triggered event (e.g., a volume of mass moving down a slope) is governed by complex physical mechanisms that are intrinsically related to the specific interactions between the triggering and the triggered events. This fact and the ubiquitous random effects that may affect these processes make probabilistic approaches the most promising way for the quantitative characterization of such interactions (e.g., Garcia-Aristizabal et al. 2015; Gasparini and Garcia-Aristizabal 2014).

The interactions described in the previous paragraph are mainly related to triggering effects between hazards. However, when the interaction between different hazards involves the response of a man-made structure (as e.g., a building, or an industrial element), then the interaction is said to take place at “vulnerability level” (see e.g., Gasparini and Garcia-Aristizabal 2014; Garcia-
Aristizabal et al., 2015). This perspective of the cascading effect problem fundamentally intends to assess the effects that the simultaneous occurrence of two or more events (not necessarily linked among them) may have for the final risk assessment. In this case, the action of different hazards is considered and combined at the vulnerability (or damage) level, and the main interest is to assess the effects that the occurrence of one event (the first one occurring in time) may have on the response of the exposed elements against another event (that may be of the same kind as the former but also a different kind of hazard). Examples of this kind of interactions have been presented in literature, for example, in Lee and Rosowsky 2006, Zuccaro et al. 2008, and Marzocchi et al. 2012.

2.2 Multi-risk assessment applied to shale gas operations: overview

The description of the probabilistic approach used for the multi-risk assessment is the main objective of the forthcoming deliverable D7.2. In this section we provide a very general conceptual overview of the multi-risk problem applied to shale gas operations, so that the reader gets familiar with the terminology and understands the importance of identifying and structuring scenarios for the multi-hazard/multi-risk analysis.

The main objective of a multi-hazard/multi-risk assessment applied to shale gas operations is to identify and to assess the rate (or the likelihood) of occurrence of incidents, and their potential impacts on surrounding environment, considering different hazards and their interactions. Furthermore, such analyses have to be performed considering the different stages of development of a shale gas project.

According to this general objective, the implementation of a multi-hazard/multi-risk assessment applied to shale gas operations needs to take into account different issues as the following:

1. It has to take into account the possibility of multiple (natural and anthropogenic) hazards as possible triggering mechanisms;
2. It has to explore all the plausible scenarios of cascading events, identifying the logical relationships among the different events driving to an unwanted consequence;
3. It has to assess the possibility of impacting different typologies of environmental and anthropic exposed elements.

The multi-risk assessment applied to shale gas operations poses a number of challenges, making of this one a particularly complex problem. First, a number of external hazards might be considered as potential triggering mechanisms. Such hazards can be either of natural origin, occurring underground (as e.g., natural earthquakes), in the atmosphere (as e.g., extreme meteorological events) or at the air/ground interface (as e.g. landslides), or anthropogenic events caused by the same industrial activities (as e.g., subsidence, triggered and induced seismicity). Second, failures might propagate through the industrial elements, leading to complex scenarios according to the setting of the industrial site. Third, there is a number of potential risk receptors, ranging from environmental elements (as the air, soil, surface water, or groundwater) to local communities and ecosystems.

Considering the typology of problems faced in risk assessments involving industrial activities, a quantitative risk analysis can be structured in the following main steps (see e.g., Rausand and Hoyland 2004):

1. The identification and description of potential accidental events in the system: An accidental event is usually defined as a significant deviation from normal operating conditions that may lead to unwanted consequences. In the oil/gas industry, for example, a gas leak may be defined as an accidental event.
2. The potential causes of each incidental event are identified by *causal analysis*. The causes are usually identified in a hierarchical structure that may be described using a *fault tree*. If probability estimates are available (of the basic events), these may be input to the fault tree and the probability/frequency of the accidental event may be calculated.

3. Most industrial systems include various barriers and safety functions that have been installed to stop the development of accidental events or to reduce their consequences. The consequence analysis is usually carried out using an *event tree* analysis.

These general steps for the quantitative risk assessment can be represented using a so-called “bow-tie” (BT) structure. This approach have been proposed for assessing risks in a number of applications in the field of georisource development, as for example in offshore oil and gas development (e.g., Khakzad et al., 2013, 2014; Yang et al., 2013) and for the mineral industry in general (e.g., Iannacchione, et al., 2008). We consider that such an approach constitutes a valid tool for developing a multi-risk assessment framework for shale gas operations. The multi-hazard/multi risk approach for this problem is set by considering multiple hazards (and their possible interactions) as possible sources of system's perturbation that might drive to the development of an incidental event.

The BT is a graphical tool that facilitates structuring accident scenarios, starting from the accident causes and ending with the consequences. It is targeted to assess the causes and effects of specific critical events (also called “top events”). It is composed of a fault tree (FT) on the left hand side of the graphic plot, identifying the possible events causing the critical (or top) event, and an event tree (ET) on the right-hand side showing the possible consequences of the critical event (Fig. 1).

**Fig 1. Generic representation of a Bow-tie**

Combining *fault trees* and *event trees* in a BT is a tool widely used in reliability analysis for risk assessment (see e.g., Rausand and Hoyland 2004). The definition of a BT structure requires a number of activities, starting from the definition of the critical or top event (TE). The critical TE should represent a well defined incident (e.g, what happens and where it happens) and is the endpoint of a number of possible paths represented in the FT. Furthermore, the TE represents the starting point of an ET, which in turn is used to model the potential consequences that the occurrence of that specific incident may have on a number of exposed elements of interest.
Given the complexity of the problem, we adopt a multi-level approach (as e.g., Liu et al. 2015) in which we first perform a qualitative analysis oriented to the identification of a wide range of possible scenarios. This process is based on a wide literature review of potential impacts in different risk receptors of interest and is condensed in a number of causal diagrams as those shown in this report. Second, the most important scenarios for quantitative multi-risk analyses are selected for further quantification. This selection is based on the identification of major risks, i.e., those related with the occurrence of low probability/high impact extreme events (therefore, the impacts associated with routine activities are not considered). Finally, the selected scenarios are structured for quantitative analysis following the model for quantitative assessments (to be presented in Deliverable 7.2).

In the multi-hazard/multi-risk analysis in SHEER we are interested in considering multiple categories of risk receptors, which range from environmental to community disruptions caused by a shale gas development project. For convenience in the modeling process, we arbitrarily divide the possible risk receptors in two groups: “Primary risk receptors” and “Final risk receptors”.

2.2.1 Primary risk receptors (PRR)

According to our division of risk receptors and the strategy adopted for structuring scenarios, the primary risk receptors in this case are basically the environmental elements that potentially might be affected by the industrial activity associated with a shale gas development project. Considering the elements of interest for the SHEER project, therefore, the primary risk receptors are (1) the atmosphere (air), (2) the groundwater, and (3) the surface water.

2.2.2 Final risk receptors (FRR)

The final risk receptors are those that potentially can be impacted either indirectly by the impacts in a primary risk receptor, or directly by the effects of the industrial activity. Clearly, there are two main categories of final risk receptors: (1) the communities (that includes the building environment and the society) and (2) the ecosystems localized in the surroundings of a shale gas development project. Regarding in particular the community disruption, the impacts do not pertain only to the physical domain but also to the socio-economic domain. For this reason, parallel to the assessment of effects in physical elements (such as buildings and infrastructure), impacts in final risk receptors can also embrace the socio-economic effects.

The assessment of secondary impacts on final risk receptors requires the characterization of both the physical vulnerability to specific hazard sources or primary receptors and the exposure of a community surrounding a shale gas site.

2.3 Integrating socio-economic impacts: overview

In general, socio-economic effects associated with shale gas operations might be framed in terms of opportunities and risks. In the short term, the development of unconventional gas may generate positive effects on employment. Jacobsen and Parker (2014) for example, examined the effects of the boom-and-bust cycle of the 1970s and 1980s, finding that the boom created substantial short-term economic benefits, transforming in joblessness and depressed local incomes in the long run. However, present data on shale gas development are poor as the shale boom started just few years ago, causing the assessment of possible busts to be difficult to evaluate.

Given that the main objective of the multi-risk analysis is focused on analyzing major risks associated with extreme events causing incidents, the socio-economic analysis will be is mainly focused on risks, rather than on the opportunities. With this aim, a research of key indicators useful for socio-economic analyses has been activated. Those indicators rely on multi-dimensional information considering different parameters related, for example, with the main economic
activities in the examined area, the employment levels in different economic sectors and unemployment rates, the population structure and density, households, risk perception, healthcare expenses, housing prices, etc.

The identification of indicators needs to consider the impact scenarios considered in a given study area, and the site-specific socio-economic context indicators. The scheme in Fig. 2 shows a brief example of how the impacts in different elements (basically primary risk receptors as e.g., water contamination, induced seismicity, and air pollution) can be considered from the socio-economic perspective for the SHEER hazards.

Fig 2. Example of possible indicators useful for assessing socio-economic impacts derived from impacts in different primary risk receptors.

For example, water contamination is one of the most perceived risk by population. Housing prices and prices per hectare-agricultural land are two key indicators for the quantifying socio-economic effects of water contamination. In fact, the access to a safe and reliable source of drinking water is a key parameter to be taken into account to determine property values. Muehlenbachs et al. (2015) finds that groundwater dependent homes face large adjacency risk when the property is very close to the well and that the groundwater contamination risk is large and significant, potentially causing a drop in the housing value. The socio-economic evaluation associated with low-magnitude induced seismicity may be pursued, for example, assessing indicators of tangible indirect effects related with public concern (it is worth noting that the identification and assessment of such indicators is an ongoing activity). Considering a higher magnitude (and less likely) event, it may be possible to consider the possible effects that disruptions can have on indicators (as e.g., the effects on working hours of people employed in a determined area).

2.4 Identification and structuring of risk pathway scenarios

There are two key elements for developing scenarios for a multi-hazard/multi-risk analysis based on a bow-tie structure (see e.g., Fig. 1): first, the identification of the possible top events, and second the identification of the source events.

The identification of the critical top events is a fundamental step when developing fault tree analyses. In fact, the fault tree analysis is a deductive technique starting with a given failure or accident. It is very important that the TOP event is given a clear and unambiguous definition. If not, the analysis will often be of limited value. Different configurations of fault trees can be constructed for a given system, depending on the typology of top event and the basic events considered for the analysis.
Given the different categories of risk receptors previously defined, the following criteria have been used for structuring scenarios:

1. Impacts in primary risk receptors have been chosen as critical top events for constructing fault trees. These have to be well specified events (e.g., what and where it happens?). An example of a top event is “pollution of groundwater due to in-site leakage of fluids”.

2. Identification of the boundary conditions with respect to external stresses. In this way, we define the type of external hazards that are going to be included in the analysis.

3. For each top event identified, a deductive technique is used to identify the possible causes of such failure, considering the boundary conditions defined and the level of resolution of the analyses.

4. The identified top events are also the starting points of consequence analysis, which is evaluated for considering the impacts on a final risk receptors of interest. Such analyses will be structured using an event tree approach.

Keeping in mind such criteria for structuring scenarios, the first step for the multi-hazard/multi-risk analysis is the identification of the possible scenarios, which is the main purpose of this deliverable.

There exist a number of approaches for identifying and structuring relevant risk pathway scenarios, most of which are based on either forward or backward logic approaches, or a combination of both (e.g., Garcia-Aristizabal et al., 2014). The former approach follows a forward logic in the sense that for each initiating event, it identifies the possible outcomes (endpoints), following an event-tree-like structure. The backward logic strategy begins with an endpoint (effect) and works backwards to find the most likely causes of the effect, following a fault-tree-like structure. The combination of both approaches (adaptive approach) stems from the idea to iteratively use the forward logic and the backward logic approaches, and combine the results obtained in order to exhaustively identify all the relevant scenarios for the specific problem at hand.

Conceptually, to identify the risk pathways in a multi-risk approach we take into account possible Source-Mechanism-Receptor (SMR) linkages. In this context, a risk pathway starts from an initial, triggering event (Source) that subsequently develops in a chain of events upon causing an impact in a given risk receptor. The Mechanism defines the means of risk transfer from the source to the receptor, where the risk receptor is the element exposed to risk that can be impacted by the activity. The advantage of this approach is to define a logical subdivision of interrelated events leading to a given impact on the environment.

It is worth noting that from the multi-risk assessment point of view, all these three elements (SMR) are important (Fig. 3): a Receptor, which is the element exposed to risk and that we have divided in “Primary” (mainly environmental) and “Final” receptor (related with the final disruption potentially caused); a Mechanism, which defines the means of risk transfer from the source to the receptor; and the Source, which is the event causing the initial conditions potentially driving to adverse consequences (incidents).

As a first step for the scenario identification process, we have analyzed relevant literature in order to put in evidence those scenarios more recurrently claimed as of priority for risk analyses for shale gas development. This initial screening allowed us to define a number of categories for each element of the SMR pathway, which in summary are (see Fig. 3):

– two categories for the final receptors, namely: Community disruption (as e.g., health, noise, lights, traffic, etc.) and ecosystem disruption;

– three categories for primary receptors (namely: surface water, ground water, and air quality).

– Regrating the mechanisms acting for transferring the risk from the source to the receptor, these are of course related to the specific pathway from a given source to a given receptor.
In practice, these may include events as casing failure, underground or surface blowouts and leaks.

- The possible sources acting as triggering mechanism for a chain of events are both natural (as e.g., earthquakes or subsidence) and technological (drilling, hydraulic fracturing, or other routine operations) in origin.

![Diagram](image)

Fig 3. Source-Mechanism-Receptor links defining a risk pathway associated with shale gas development.

It is worth noting that the source events and the category of risk receptor impacted by the industrial activity may change according with the stage of a project development. Therefore, it is necessary to identify scenarios for each phase of the project. For our analyses, we have divided the life-cycle of a project in 5 stages that are briefly described in the following section.
3 Phases in a shale gas project development

The potential pathways identified from literature reports were collected and grouped according with the stage of a project (well-pad) development for which they are relevant. We defined the following five stages: (1) Site development and drilling preparation; (2) Drilling activities; (3) Fracturing and well completion; (4) Production and operation; (5) Well abandonment and post-abandonment (Fig. 4).

### 3.1 Site development and drilling preparation

Once a site has been identified, land is needed to set the well-pad and for supporting infrastructure as roads, pipelines and storage facilities. Land disturbance directly associated with high-volume hydraulic fracturing consists primarily of constructed gravel access roads, well pads and utility corridors. According to the New York State Department of Environmental Conservation report (New York State DEC, 2011), the average total disturbance associated with a multi-well pad, including incremental portions of access roads and utility corridors, during the drilling and fracturing stage is estimated at 30 hectares (but in the long-term production phase, a multi-well pad itself would occupy about 5 hectares).

The first step in developing a natural gas well site is to construct or adjust the access road and well pad. Access road construction (usually 6 to 12m during the drilling and fracturing phase and from 3 to 6m during the production phase) involves clearing the route and preparing the surface for movement of heavy equipment, or reconstruction or improvement of existing roads if present on the property being developed. Ground surface preparation for new roads typically involves staking, grading, stripping and stockpiling of topsoil reserves, then placing a layer of crushed stone, gravel, or cobbles over geotextile fabric. Sedimentation and erosion control features are also constructed as needed along the access roads. The size of the access road is dictated by the size of equipment to be transported to the well site, distance of the well pad from an existing road and the route dictated by property access rights and environmental concerns. The route selected may not be the shortest distance to the nearest main road. Routes for access roads may be selected to make use of existing roads on a property and to avoid disturbing environmentally sensitive areas such as protected streams, wetlands, or steep slopes (New York State DEC, 2011).

Pad size is determined by site topography, number of wells and pattern layout, with consideration given to the ability to stage, move and locate needed drilling and hydraulic fracturing equipment. Location and design of pits, impoundments, tanks, hydraulic fracturing equipment, reduced emission completion equipment, dehydrators and production equipment such as separators, brine tanks and associated control monitoring, as well as office and vehicle parking requirements, can increase square footage. Mandated surface restrictions and setbacks may also impose additional acreage requirements Site preparation activities consist primarily of clearing and leveling an area of adequate size and preparing the surface to support movement of heavy equipment. Site preparation
also includes establishing erosion and sediment control structures around the site, and constructing pits for retention of drilling fluid and, possibly, fresh water. Industry estimates the average size of a multi-well pad for the drilling and fracturing phase of operations at 14 hectares, whereas the average production pad size is estimated at 6 hectares for a multi-well pad (New York State DEC, 2011). Finally, utility corridors associated with high-volume hydraulic fracturing will include acreage used for potential water lines, above ground or underground electrical lines, gas gathering lines and compressor facilities (New York State DEC, 2011).

3.2 Drilling activities

Except for the use of specialized downhole tools, horizontal drilling is usually performed using similar equipment and technology as vertical drilling. Furthermore, in US the same protocols in place for aquifer protection, fluid containment and waste handling are used for both vertical and horizontal drilling (New York State DEC, 2011). Wells for shale gas development using high-volume hydraulic fracturing are drilled with rotary rigs. Operators may use one rig to drill an entire wellbore from the surface to toe of the horizontal bore, or may use two or three different rigs in sequence. At a multi-well site, two rigs may be present on the pad at once, but more than two are unlikely because of logistical and space considerations (Broomfield 2012). The first drilling stage is to drill, case, and cement the conductor hole at the ground surface. This process takes approximately 1 day, with the depth and size of the hole depending on the ground conditions. A vertical pipe is set into the hole and grouted into place. The second drilling stage is to drill the remainder of the vertical hole. This can take up to 2 weeks or longer if drilling is slow or problems occur. A surface casing is constructed which extends below the lowest aquifer and is sealed to the surface. Additional casing should be provided for the surface layers (New York State DEC 2011; Broomfield 2012). A further intermediate casing extends to the top of the hydrocarbon-bearing formation. Cement is pumped between the intermediate casing and the intervening formations to isolate the well bore from the surrounding rock, act as a barrier to upward migration through this space, and provide support to the intermediate casing. The third drilling stage is to drill the horizontal bore. Again, this stage would take up to 2 weeks or longer if delays occur. This gives a total duration of the drilling stage of up to 4 weeks (Broomfield 2012). The production casing extends into the shale gas formation itself and along the horizontal bore. In other cases, “open hole” completions are carried out, in which the production casing penetrates the top of the producing zone only. No casing is provided for the horizontal section of the wellbore within the production zone. Once the cement hardens, shaped charges are pushed down the pipe to perforate the pipework and cement layer at the required locations. The last steps prior to fracturing are the installation of a wellhead which is designed and pressure-rated for the fracturing operation. The system is then pressure tested (New York State DEC 2011; Broomfield 2012).

3.3 Hydraulic fracturing and well completion

When perforations are present at the appropriate point, fracturing fluid is pumped into the well at high pressure. Hydraulic fracturing procedures are designed taking into account the rock properties of the hydrocarbon reservoir. The proppant is forced into the fractures by the pressured water, and holds the fractures open once the water pressure is released. For conventional fracturing, the fracture pressure gradient is typically 0.4-1.2 psi/foot (0.09 – 0.27 bar/meter). The range of fluid pressures used in high volume hydraulic fracturing is typically 10,000 to 15,000 psi (700 – 1000 bar), and exceptionally up to 20,000 psi (1400 bar). This compares to a pressure of up to 10,000 psi (700 bar) for a conventional well (Broomfield 2012). Fracture lengths can be expected to vary
depending on the geological properties of the rock matrix and the fracture treatment. The objective in any hydraulic fracturing procedure is to limit fractures to the target formation. Excessive fracturing is undesirable from a cost standpoint because of the expense associated with unnecessary use of time and materials (water, additives and proppants, as well as the need for fluid storage and handling equipment). In addition, if adjacent rock formations contain water, then fracturing into them would bring water into the reservoir formation and the well. In literature, a maximum fracture length from several thousand shale gas fracturing operations in the US have been estimated between 588 and 600 meters, whereas most of the fractures have been less than 100 m (e.g., Davis et al., 2012; Fisher and Warpinski 2012).

After the hydraulic fracturing procedure is completed and pressure is released, the direction of fluid flow reverses. The well is "cleaned up" by allowing water and excess proppant to flow up through the wellbore to the surface. Both the process and the returned water are commonly referred to as “flowback” (New York State DEC 2011). Flowback fluids include (1) the fracturing fluids pumped into the well, which consists of water and additives, (2) any new compounds that may have formed due to reactions between additives and (3) substances mobilized from within the shale formation due to the fracturing operation. Hydraulic fracturing wastewater may be stored in tanks or pits prior to disposal or recycling. A number of options exist or are being developed for treatment, recycling and reuse of flowback water. Nevertheless, proper disposal is required for flowback water that is not reused. Factors which could result in a need for disposal instead of reuse include lack of reuse opportunity (i.e., no other wells being fractured within reasonable time frames or a reasonable distance), prohibitively high contaminant concentrations which render the water untreatable to usable quality, or unavailability or infeasibility of treatment options for other reasons. Common potential flowback water disposal options considered are (1) injection wells, (2) municipal sewage treatment facilities (POTWs); and (3) industrial treatment plants (New York State DEC 2011).

3.4 Production and operation

Before gas production can commence, pipeline infrastructure must be developed to collect natural gas for transfer to the existing natural gas pipeline infrastructure. Once the well is connected to the gas main, gas can be dehydrated, and then passed to the collection system. Ongoing maintenance and monitoring is required to confirm that the gas production process is proceeding satisfactorily without adverse environmental or health effects (Broomfield 2012). The flow to the well can be expected to decrease rapidly following the initial phase.

3.5 Well abandonment and post-abandonment

When the well is no longer economic to operate, it is taken out of service temporarily or permanently. Abandonment takes place in accordance with established procedures in the oil and gas production industry. Abandonment procedures for use in the conventional oil and gas industry in Europe have been specified by national regulators (e.g. Norsok Standard D-010 is applied in Norway; see also Oil and Gas UK 2012 NPR). Abandonment procedures include the installation of a surface plug to stop surface water seepage into wellbore. A cement plug is installed at the base of the lowest underground source of drinking water to isolate water resources from potential contamination by hydrocarbons or other substances migrating via the wellbore. A cement plug is also installed at the top of the shale gas formation (Broomfield 2012). In the post-abandonment phase, the most relevant activity is the assessment of potential impacts over short-medium timescales and long timescales. Over short-medium timescales of decades, it is assumed that management and maintenance regimes will be in place. Over long timescales (of hundreds of
years), potentially management and maintenance regimes will no longer be in place (Broomfield 2012). There is generally little difference between conventional and unconventional wells in the post-abandonment phase, with the exception of the presence of unrecovered hydraulic fracturing fluids in the shale formations in the case of hydraulically fractured wells (Broomfield 2012).

4 Identifying and structuring pathway scenarios for MR assessment

The identification of environmental impacts associated with shale gas development is usually done by describing the (generally adverse) effects of such activities in a number of possible exposed elements. In our approach we first analyzed information about potential impacts as found in specialized literature in order to structure possible risk pathway scenarios. To identify risk pathways we take into account possible Source-Mechanism-Receptor (SMR) linkages adopting a multi-risk perspective, as described in Section 2.4.

There exist a considerable amount of peer- and (mostly) non peer-reviewed literature suggesting different possibilities of environmental impacts associated with shale gas development. From these reports, a number of possible risk pathways associated with shale gas development can be identified. After filtering the most relevant literature, a total of 50 publications were considered in this study. The full list of references of the considered literature is found in the Annex A. Analyzing the typology of impacts described in literature, we have identified and categorized six typologies of risk receptors that, as described in section 2.4, we arbitrarily divided in two general categories: primary risk receptors, associated mainly with environmental issues, and final risk receptors, related mainly with the disruption caused specifically to a community or ecosystem. This differentiation is useful because the impact pathways driving to primary risk receptors can be almost fully considered from a physical point of view, whereas those considering the final receptors may have both a physical and socio-economic dimensions.

Regarding the analyzed literature, it results evident that each publication or report is generally oriented towards describing a limited number of mechanisms and/or taking in consideration specific risk receptors. As a reference, Table 1 shows the percentages of papers/reports dealing with impacts in the different risk receptor categories. Peer reviewed and non-peer reviewed literature is considered separately. For example, the 19.5 value in the leftmost cell of the first row indicates that 19.5% of the examined peer-reviewed literature deals with pollution of surface water as an impact of shale gas operations. In general, peer-reviewed articles tend to focus in specific problems which are generally handled with greater detail and often in quantitative terms. Conversely, general reports (peer- and non-peer-reviewed) tend to be more qualitative, presenting generic descriptions of a wide variety of potential impacts.

A screening of risk scenarios has been performed considering the most recurrent issues evidenced in specialized literature. The scenarios have been divided by project development stage. In total, 56 pathway scenarios (considering either impacts caused by ordinary routine operations, and those caused by incidents due to system failures or extreme events) were identified. Classified by project phase, those scenarios are divided as follows: 11 scenarios were identified for the site development and drilling preparation phase; 7 scenarios for the drilling activities; 21 scenarios for the fracturing and well completion phase; 11 scenarios for the production and operation phase; and 6 scenarios for the well abandonment and post-abandonment phase.
Table 1. Summary of literature used for the identification of risk pathway scenarios (a complete list is provided in Annex A). The percentage values showed in this table are referred to the percentage of related literature (row) in which the respective risk receptor (column) is considered. Soil quality is included as possible primary risk receptor as well, but not considered for the structuring of scenarios in this work.

<table>
<thead>
<tr>
<th>Primary Receptor</th>
<th>Final Receptor</th>
<th>Number of publications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface water (%)</td>
<td>Ground water (%)</td>
<td>Air quality (%)</td>
</tr>
<tr>
<td>Peer-reviewed papers and reports</td>
<td>19.5</td>
<td>28.7</td>
</tr>
<tr>
<td>Non peer-reviewed reports</td>
<td>21.1</td>
<td>23.7</td>
</tr>
</tbody>
</table>

*41 documents, from where 37 peer reviewed papers and 4 peer-reviewed reports.

Those risk pathway scenarios are described in the following paragraphs divided by the stage of the project development. For each stage, a causal diagram representing the full range of scenarios identified (i.e., covering impacts associated with both routine and incidental events) have been created. In all those diagrams (Figs. 5 To 9), dark gray circles identify events associated with ordinary routine operations, while white circles identify events associated with incidents and/or extreme events.

These causal diagrams are the base for identifying scenarios for quantitative proposes. Such quantitative development will be the focus of D7.2 (at M24 after the project start). Temporal (short-term and long-term) and spatial domains will be constrained when setting the probabilistic framework.

4.1 Risk pathways identified for the site development and drilling preparation phase

Figure 5 shows a causal diagram with the main risk pathway scenarios identified for the site development and drilling preparation phase. Most of the identified pathways correspond with environmental impacts associated with routine activities. The primary risk receptors mostly involved in this phase are the air and the surface water. Air is mostly affected by routine activities as emissions from vehicles and site construction equipment operating for road construction and well-pad site preparation. Surface water bodies can be affected by different ways, but the most common causes being the runoff and erosion (associated with road and well-pad construction) and potential vehicle accidents the most commonly cause (see Annex A for references of background literature).
A number of phenomena directly impacting final risk receptors have been also identified. In particular, noise caused by equipment and vehicles and ground vibrations may cause disruptions to communities and ecosystems. On the other hand, the construction of roads may produce habitat fragmentation. Noise and emissions due to vehicle transportation are also potential impacts associated with new/existent roads.

Regarding the pathways of possible interest for risk assessment, only one of the scenarios has been selected as potentially associated with incidents or extreme events, and is related with the pollution of surface water caused by potential accidents of vehicles transporting chemical material.

4.2 Risk pathways identified for the drilling phase

Figure 6 shows a causal diagram with the main risk pathway scenarios identified for the drilling phase. Different pathways impacting primary risk receptors (air, surface- and ground-water) have been identified. Considering the scenarios driving to incidents, the main possible pathways are related to surface or underground blowout events caused by uncontrolled kick events of by potential lost circulation caused by finding high permeability zones. Another source of incidental scenarios are associated with damages in storage facilities (see Annex A for references of background literature).
For the objectives of the SHEER project, this set of scenarios is probably that of principal importance, since it encloses all the possible pathways specifically associated with the hydraulic fracturing activities. Therefore, in this group we may find the phenomena that are more likely different to conventional exploitation activities. Figure 7 shows the pathways identified for the fracturing and well completion phase. Effects in final risk receptors can be associated with direct effects of events derived from hydraulic fracturing operations (mainly by induced seismicity) or through impacts to primary risk receptors (in particular impacts to surface water, groundwater and air).
Fig 7. Risk pathways identified for the fracturing and well completion phase (dark circles identify events associated with ordinary routine operations, and white circles identify events associated with incidents).

Regarding the scenarios associated with incidents or extreme events (relevant for risk assessment), a number of pathways can be outlined. For example, surface water and ground water can be both affected either by on-site spills caused by loss of containment, fluid transport, or by flowback/waste water disposal. Possible ground water pollution has been also associated to fluid migration from target formation, casing damage, or, in the case of underground injection of flowback and waste water, by fluid migration from injection formation. Finally, induced seismicity can be associated with both hydraulic (see e.g., Atkinson, et al., 2016) fracturing and waste water injection (see e.g., Weingarten et al., 2016; Ellsworth et al., 2015). Annex A for references of background literature.

4.4 Risk pathways identified for the production and operation phase

Figure 8 shows a causal diagram with the main risk pathway scenarios identified for the production and phase. For this phase, the main primary risk receptors identified as potentially impacted by incidents or extreme events are the surface water and the groundwater. As for other phases, the mechanisms are mainly associated with loss of containment, fluid transport accidents (in the case of off-site transport of waste water). Induced seismicity can be associated with eventual underground disposal of waste water or by deformation processes caused by depletion (see Annex A for references of background literature).
Fig 8. Risk pathways identified for the production and operation phase (dark circles identify events associated with ordinary routine operations, and white circles identify events associated with incidents).

4.5 Risk pathways identified for the well abandonment and post-abandonment phase

Figure 9 shows a causal diagram with the main risk pathway scenarios identified for the abandonment and post-abandonment phase. In this case, the outlined scenarios are mainly associated to long-term processes of depletion, which may have the potentiality of producing induced seismicity. More remotely, a scenario in which depletion causing damages in the well bore may drive to fluid migration and groundwater pollution has been also outlined (see Annex A for references of background literature).
Fig 9. Risk pathways identified for the well abandonment phase (dark circles identify events associated with ordinary routine operations, and white circles identify events associated with incidents).
5 The path forward

Figures 5 to 9 represent causal relationships among a number of events which show possible pathways potentially leading to impacts in both primary and final risk receptors. Such causal relationships are the base for structuring the scenarios for quantitative multi-risk analyses. As outlined in section 2.4, for quantitative purposes these scenarios are going to be structured following a bow-tie method, in which impacts to primary risk receptors will constitute the base for identifying critical top events, and multiple hazards will constitute the base for identifying basic events. Figure 10 shows an example of the passage from the causal diagram outlined in a generic stage of a project (Fig. 10a) and the respective set of scenarios structured following a bow-tie approach for a given critical top event of interest (Fig. 10b). Such a find of structure is the reference point for the quantitative muti-risk analysis. The multi-hazard component is structured using a fault tree structure (Fig. 10c); the top event of the fault tree is linked to a primary risk receptor (Fig. 10d) which, in turn, is the basic event for the fault tree structure used for assessing consequences (Fig. 10e and 10f). The consequences are considered taking into account physical (Fig. 10e) and socio-economic impacts (Fig. 10f).

Fig 10. Example of the passage from the causal diagram towards the structuring of a set of scenarios following a bow-tie structure. (a) causal diagram of the identified scenarios; (b) bow-tie structure implemented for a given critical top event of interest (for details see the text)
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Weingarten, M., S. Ge, J. W. Godt, B. A. Bekins, J. L. Rubinstein (2015), High-rate injection is associated with the increase in U.S. mid-continent seismicity, Science 348 (6261), 1336-1340. DOI: 10.1126/science.aab1345


Appendix A

Summary of the literature considered for identifying and structuring the risk pathway scenarios described in this report. This list contains 47 references that were selected after filtering a number of papers and reports related to environmental impacts associated with shale gas operations. The selected documents were divided in three groups, namely: peer-reviewed papers, peer-reviewed reports, and non-peer-reviewed reports.

A.1 Peer reviewed papers


35. Weingarten, M., S. Ge, J. W. Godt, B. A. Bekins, J. L. Rubinstein (2015), High-rate injection is associated with the increase in U.S. mid-continent seismicity, Science 348 (6261), 1336-1340. DOI: 10.1126/science.aab1345


A.2 Peer reviewed reports


A.3 non peer-reviewed reports


49. Broomfield, M. (2012). Support to the identification of potential risks for the environment and human health arising from hydrocarbons operations involving hydraulic fracturing in

50. Groat, C. G., T. W. Grimshaw (2012). Fact-Based Regulation for Environmental Protection in Shale Gas Development: Summary of Findings. A report by the Energy Institute, Flawn Academic Center, FAC 428, 2 West Mall, C2400, The University of Texas at Austin, Austin, TX 78712