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Availability study of an installation dedicated to CO2 capture, optimization of the design and of the injection strategy via Petri nets

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In recent years, the fact that environmental constraints increases has prompted all sectors of industry to reduce their greenhouse gas emissions and limit the impact of their activities on the environment.

TotalEnergies is one of the companies the most committed to reducing emissions, primarily through innovation in the field of CO2 capture and injection. The underlying idea is quite simple: converting disused gas production reservoirs into CO2 storage.

Several projects in the North Sea have recently been launched. The main principle of the process is to transport liquid or gaseous CO2 to facilities located close to the sea, download, regas (partially) and compress the gas and then inject it under pressure into a storage reservoir via disused production wells.

Keywords: Petri nets, CO2 Injection, CO2 Capture, Sustainable development, Production availability.

1. Introduction

The subject of the research presented in this paper is unique in many respects not only because it is being carried out jointly with other industrialists, but also since both the chemical composition of CO2 is different from the one of production gas, numerous constraints must be taken into account in order to preserve the reservoir.

The CO2 injected comes from two different sources, in gaseous form (from compression) or in liquid form (transported by ship). Mixing these two types of CO2 results in a new composition that will be injected into disused production wells. However, since the nature of the reservoir does not allow for continuous injection, injectivity envelopes linked to the composition of the CO2, temperature and pressure in the well must be considered.

Since it is a new type of project, the main issues to address are profitability and, from a technical point of view, the injection capacity of the wells. In order to answer these questions, a production availability study (see [ISO 20815]) was carried out based on a Petri net model.

2. Context

2.1. New challenges for TotalEnergies

Preparing for the energy transition is a key issue for the French government which enacted the Law on Energy Transition for Green Growth (LTECV) on 17 August 2015 to limit global warming. To address this climate imperative, French energy industry giant Total became TotalEnergies in 2021 to establish itself as a major player in the energy transition and to achieve, alongside society, carbon neutrality by 2050.

To this end, the company set itself the following objectives:

(i) To reduce its greenhouse gas emissions as much as possible, primarily at sites in Europe and elsewhere in the world for which the Company is directly responsible.
(ii) To compensate for all remaining emissions, for instance through CO2 capture solutions.
(iii) To provide an energy mix that is less and less carbon intensive, thanks to the development of renewable energies (solar, hydrogen, onshore and offshore wind power, etc.).

2.2. The Aramis project

Carbon storage is a key element in achieving carbon neutrality and TotalEnergies is developing initiatives aimed at preserving and restoring ecosystems that act as carbon wells capable of absorbing CO2 from the atmosphere.

It is in this context that TotalEnergies and its partners are developing the Aramis project in the Netherlands to store liquefied CO2 transported from the port of Rotterdam to depleted offshore gas fields. As with all TotalEnergies projects, the deliverables of this project include a detailed availability study of the system.

Fig 1. Aramis project

2.3. Study objectives, scope and issues

The main objectives of this availability study, also called PAS in TotalEnergies for Production Availability Study, are:

- To determine the production availability (or rather injection availability) of the installations in relation to a given maximum potential.
- To identify the weak points of the system, whether they are specific process equipment items/units, utilities, or operational constraints.
- To carry out sensitivity studies to be able to provide recommendations to project team that could optimise the architecture, the operating and/or the maintenance philosophy of the installation.

All potentially critical equipment for the performance of the installation must be considered, as well as all the associated operational constraints (logistical delays, resources, restart times, preventive maintenance, safety tests, etc.). The scope of the study ranges from the unloading arms located on the jetty through which the liquefied CO2 will be delivered to the subsea injection wells, including the onshore storage tanks, the regasification unit, all compression systems, and all utilities. It should be noted that all potentially critical processes as well as safety valves and sensors must also be considered (subsea and topside).

In fine, the purpose of the study is essentially to test and verify the architecture of the plant (redundancy of the various units, sizing of the storage tanks, etc.) as well as project operating philosophy, especially regarding the injection wells, as this is a relatively complex aspect to set up and model.

3. Project constraints

The Aramis project is in many ways an innovative project. Its primary objective is to use former gas production wells in the North Sea to inject CO2 into them.

3.1. Two different sources of CO2

CO2 is delivered to the facility from two different sources:

- Liquid source: liquefied CO2 transported by ship from other industrial sites;
- Gaseous source: CO2 in the form of gas from on-site compression trains.

Depending on the source, the physical properties of CO2 are different, and this parameter has been taken into account in the study. For instance, CO2 transported by ship is considered pure, i.e. 100%wt CO2, whereas CO2 from compression is composed of 95%wt CO2

The proportion of each source is used to calculate the composition of the CO2 inside the trunkline and thus to define the storage wells' injection envelope, which also depends on the ambient temperature and the quantity already injected.

This composition is a dynamic composition and must be calculated in real time (every hour) to understand the progressive changes in composition in the event of a disrupted flow.

For instance, in case of a total shutdown of the liquid flow, only the gaseous flow (95 wt% CO2) feeds the trunkline. Since the trunkline is 240 km long, 28 inches in diameter and has a volume of approximately 100,000 t, the change in composition from the current composition to 95wt% does not occur instantaneously but varies over time. It is thus necessary to be able to calculate the composition of the flow through the trunkline at each moment.

For this purpose, the following is considered:

- QLCO2 = Liquid flow (t/h) = Variable
- QGCO2 = Gas flow (t/h) = Variable

- QTCO2 = QLCO2 + QGCO2 = Total CO2 entering the trunkline
- QWCO2 = QTCO2 = Total CO2 leaving the trunkline (injection into the wells)
- VTrunkline = Mass of CO2 in the trunkline (assuming dense phase) = Fixed = 100,000 T
- CLCO2 = Liquid flow composition (%wt.) = Fixed = 100% CO2
- CGCO2 = Composition of the gas flow (%wt.) = Fixed = 95% CO2
- CHX = Instantaneous composition entering the trunkline at mixing point =

$$\frac{QLCO2*CLCO2 + QGCO2*CGCO2}{QTCO2} \quad (1)$$

- CTrunkline = Overall composition (%mol) in the trunkline
- CTrunkline (H+1) = VTrunkline*CTrunkline (H) + QTCO2*1*CHX (H) - QWCO2*1* CTrunkline (H)

With these different parameters, the CO2 composition in the trunkline is:

$$C_{Trunkline}(H+1) = \frac{V_{Trunkilne} \times C_{Trunkline}(H) + (Q_{LCO2} + Q_{GCO2}) \times 1 \times \frac{(Q_{LCO2} \times C_{LCO2} + Q_{GCO2} \times C_{GCO2})}{Q_{TCO2}} - (Q_{LCO2} + Q_{GCO2}) \times 1 \times C_{Trunkline}(H)}{V_{Trunkline}} \quad (2)$$

This formula is updated every hour.

By knowing the molecular weight of the CO2 circulating in the trunkline and considering the temperature, pressure and opening of the choke valve, it is possible to know the potential injection rate into the wells.

3.2. Geological constraints

The properties of CO2 differ from the properties of the gas that is usually extracted from the wells. As a result, there are injectivity envelopes that must be respected and a new constraint to be taken into account in the modelling.

The injectivity envelopes are linked to four different parameters, each of which impacts the amount of CO2 that can be stored in the well.

The Aramis project involves filling two reservoirs via three injection wells. The reservoirs are not identical and therefore the injectivity envelope, i.e. the minimum and maximum quantities that can be injected, are different. These levels depend on:

(i) The composition of the fluid as described in the previous paragraph.

(ii) The ambient temperature: the quantity injected is greater at an outside temperature of 4°C than at an outside temperature of 16°C.

(iii) The pressure at the head of the well, expressed in bar. This pressure depends on the opening of the choke valves. This is one of the only parameters that the operator can control to optimise the quantity injected into the reservoirs.

(iv) The pressure inside the tank is directly related to the quantity already injected into the tank. The larger the quantity injected, the higher the pressure inside the tank. Once the maximum tank pressure is reached, it is no longer possible to inject.

Table 1 shows the input data for calculating the injectivity envelope of a reservoir.

Envelope	Entry parameters			CO2 rate (MTPA)		
	WHIT (°C)	WHP (Bara)	Res. (Bara)	P.Pure CO2	97% mol CO2	95% mol CO2
1	16	70	20	1.48	1.30	0.95
2	16	70	60	1.46	1.28	0.94
17	16	150	360	1.06	1.00	0.93
18	16	150	460	0.52	0.42	0.00
23	4	70	360	0.65	0.52	0.00
24	4	70	460	0.00	0.00	0.00
35	4	150	360	1.12	1.10	1.05
36	4	150	460	0.65	0.62	0.52

Table 1. Example of injectivity envelopes

3.3. Use of renewable energy

Another challenge is the use of renewable energy to supply the different platforms with electrical power.

Each platform is equipped with solar panels coupled with wind turbines to produce the power necessary to operate the main components of the installation.

The amount of sunshine in the North Sea does not provide sufficient electrical power, so an added supply from wind turbines is necessary.

In terms of reliability, this type of component is considered relatively reliable in the model.

4. Petri net modelling

4.1. Presentation of the software used

The GRIF (= GRaphical Interface for reliability Forecasting) tool, a technology of TotalEnergies, is a software suite composed of twelve modules proposing different modelling and calculation techniques dedicated to Dependability (reliability and availability of safety and production systems).

These modules are divided into three packages:

- The Boolean package, which includes the Tree (fault trees), BFiab (reliability block diagrams), ETree (event trees), SIL (safety integrity levels), Reseda (reliability networks), RISK (risk analysis) and Bool (that links all Boolean approaches of the package) modules.
- The Markovian package composed of the Markov module (Markov graphs).
- The Simulation package, including the Petri (Petri nets), BStok (stochastic block diagrams), Petro (block diagrams for Oil & Gas systems) and Flex modules.

To model properly the CO2 injection system under study, Petri nets were selected. Indeed, this method, which has been used for availability studies within TotalEnergies for more than 20 years, also provides much freedom in modelling.

Petri nets are a graphic representation of the functional and dysfunctional behaviour of a system that can evolve over time. Subsequently, the Monte-Carlo simulation is used to obtain in-depth analyses of the system, by simulating several histories of the same system over time.

This type of approach has the advantage of being very flexible while enabling complex aspects to be modelled, in particular with the use of numerical tables to save the various information necessary to update the formulas, such as the quantity injected into the tanks and the evolution of the pressure.

4.2. Presentation

This study is the first one to be carried out on this type of installation. The question of the relevance of the reliability data was raised very quickly.

There is no feedback on similar CO2 injection projects. The choice of data was made based on TotalEnergies' specific data collection. Indeed, this collection is based on the company's own feedback on E&P and LNG assets as well as on other known databases such as OREDA (Offshore and onshore REliability DAta).

The data on the wind turbine component comes from data provided by manufacturers.

4.3. Implementation of the algorithm

For reference, the objective here is to inject a maximum amount of CO2 into two subsea reservoirs, depending on the potential envelopes. Once the achievable envelopes have been identified, the flow rate of the injection pumps is adjusted to inject at maximum potential.

Several pump configurations were studied during the project to inject in a 2x100% or 3x50% configuration and for a capacity between 1 MTPA and 4.5 MTPA.

These pumps allow for injection into both TotalEnergies and Shell reservoirs, with whom the project is shared.

The flow rate varies according to the following parameters:

- The capacity of the storage tanks, which is optimised according to the arrival of the ships delivering the liquid CO2;
- Injection capacities;
- The condition of the injection wells.

The various pieces of equipment that make up the Petri net model have been modelled considering possible failure modes, repairs, spare parts management, and other logistical aspects.

The equipment and systems interact with each other by means of variables. This first step is typical for availability studies using Petri nets.

Once the model has been created, the challenge is to optimise the pump flow rate to find the injectivity envelope that allows injection into the most depleted reservoir while avoiding over-injection into a reservoir and keeping the level of the storage tanks at an intermediate level.

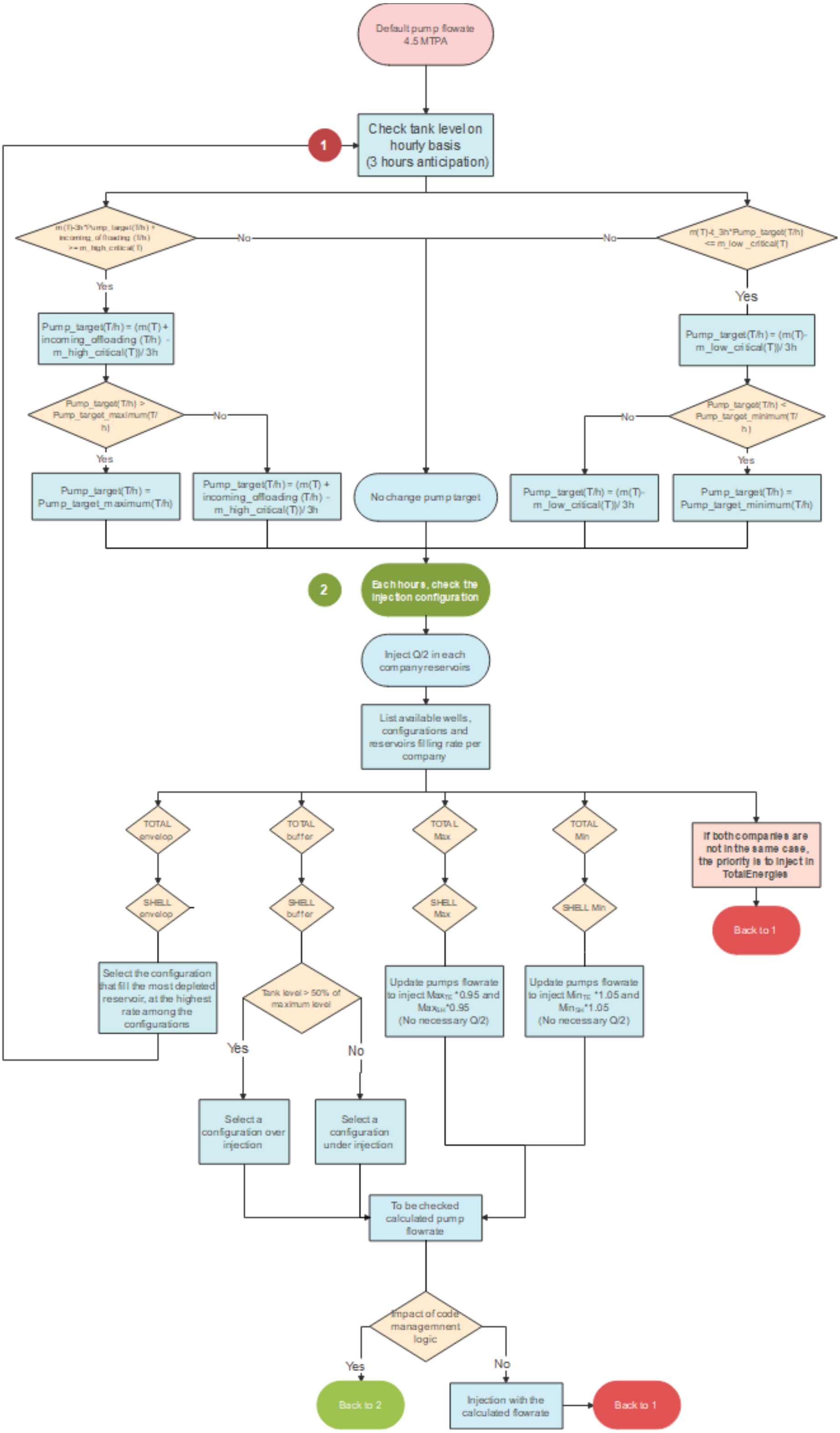

Fig. 3. Algorithm for determining the pump flow rate

The algorithm can be broken down into two steps:

- Firstly, the flow rate is calculated according to the average level of liquid CO2 in the storage tanks in anticipation of the next arrival. So, if the level is below the low limit, the flow rate will be reduced in order not to reach the lowest level of the tanks, which would lead to an interruption of the injection.
- Conversely, if the level is above the high limit, the flow rate will be increased so as not to exceed the high limit, which would also cause an interruption of the injection.
- This first flow is compared to the injectivity envelopes:
- If it is included in an envelope, it will not be updated.
- If it is not, it will be adjusted to fit within an envelope.
- If no envelope is found or all injection wells are unavailable, injection is halted.
- Each time the flow rate changes or one reservoir becomes fuller than the other, the flow rate is updated again.

Fig. 3 describes the different steps in determining the updated pump flow rate.

4.4. Modelling of 145 ship arrival scenarios

The random aspects of the arrival of liquid CO2 ships have been considered using 145 different profiles.

At the beginning of each story, one of the 145 arrival scenarios will be randomly chosen to simulate the story.

The Petri net firing transitions enable random selection between the 145 cases provided by the project. Each case corresponds to a schedule with ship arrival times and capacity.

It should be noted that if a ship cannot be fully or partially unloaded, its load is considered lost.

4.5. Validation of the method

The validation of the model is a major step, but one that is difficult to formalise for complex industrial models based on Monte Carlo simulation methods. However, the GRIF software suite uses interactive simulation to verify the behaviour of the system step by step and to bring it into conformity with the expected results. This functionality has made it possible to highlight borderline cases not dealt with by the algorithm, and thus to readjust the CO2 injection strategy mentioned in section §4.2.

Additional results provided by the MOCA-RP calculation engine, such as the average time spent in the different places, or the average number of transitions fired, make it possible to ensure the consistency of the model, with respect to the global state of the system and the reality on the ground. However, this requires a large number of simulations to be run in order to obtain relevant indicators. In our application, 10,000 stories were launched in less than ten minutes thanks to the HPC plug-in.

5. Results

The model showed a production availability of 97.5% or a total CO2 injection of 74 MT (for confidentiality reasons, the values are only there to illustrate).

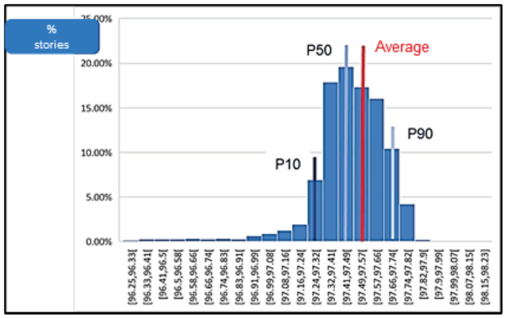

Fig 4. CO2 injection availability repartition using Monte Carlo simulation

These figures highlight the fact that the maximum injection capacity is not reached, which was one of the fears. The reservoirs are not fully entirely full at the end of the 15 years of simulations.

In terms of contribution, the main contributor is the management of the storage tanks. Indeed, if the tanks are full, the ships transporting the liquid CO2 are turned away. The second contributor is the failures and tests of the injection wells.

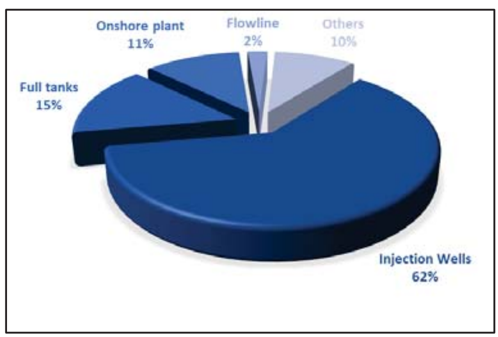

Fig 5. Main contributors injection shortfalls

During the study different configurations were considered to optimize the project design. The changes were mainly related to the size and number of storage tanks available and the capacity and redundancy of the injection pumps.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
	Tk = $40km^3$ Pu : 2x100% 4.5 MTPA	Tk = $40km^3$ Pu : 2x100% 7 MTPA	Tk = $40km^3$ Pu : 3x50% 3.9 MTPA	Tk = $50km^3$ Pu : 2x100% 4.5 MTPA
Availability	**97.4%**	**97.55%**	**97.45%**	**97.6%**
Total (MT)	**73.5**	**74.2**	**73.7**	**74.3**

Table 2. Sensitivity studies results

6. Conclusion

The availability study carried out for this CO2 injection project using Petri nets made it possible to create a model that was close to reality to test different equipment configurations, for instance by optimising the number of storage tanks or the redundancy of the injection pumps.

It also enabled us to check that it was possible to inject over a period of 15 years without reaching the reservoirs' maximum capacity, which would have resulted in halting the injection of CO2.

The various constraints were modelled to update the information required for the well injection calculations on an hourly basis.

This work is the first step. In this paper, different platforms for each company are considered as equivalent but, it's not the case.

Indeed, some injection case due to this hypothesis for the moment are not treated. For example, what happened if it is possible to inject more than the half in one field and not in the other one.

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