Provinciehuis Westerbrink 1, Assen
Postadres Postbus 122, 9400 AC Assen
www.drenthe.nl

T (0592) 36 55 55
F (0592) 36 57 77

provincie Drenthe

Aan:
de voorzitter en leden van
provinciale staten van Drenthe

Assen, 3 juli 2012
Ons kenmerk 26/3.16/201201291-00326939
Behandeld door mevrouw D. Wimmers (0592) 36 55 14
Onderwerp: CAES zoutkoepel Hooghalen

Geachte voorzitter/leden,

In de structuurvisie voor de ondergrond 'Met Drenthe de diepte in' is opgenomen dat de zoutkoepel bij Hooghalen de voorkeurslocatie is voor de eventuele ontwikkeling van een persluchtopslag, een CAES (Compressed Air Energy Storage). Een CAES reguleert de imbalans tussen elektriciteitsproductie en vraag, bijvoorbeeld in geval van variabele stroomopwekking in (grootschalige) windenergieparken. Bij een teveel aan (goedkope) elektriciteit wordt deze energie in de vorm van samengeperste lucht ondergronds opgeslagen. Bij grote (dure) energievraag wordt deze lucht weer omgezet in elektriciteit en aan het net geleverd. In het kader van haar beleid heeft Drenthe samen met Groningen en enkele andere partijen KEMA een onderzoek laten uitvoeren naar de haalbaarheid van een CAES in een zoutcaverne in Noord-Nederland.

De resultaten van dit onderzoek, 'Compressed Air Energy Storage, pre-feasibility study', zijn nu bekend. Een CAES in Hooghalen is waarschijnlijk mogelijk, maar financieel en vergunningtechnisch gezien zal de voorkeur voor een marktpartij waarschijnlijk uitgaan naar een locatie in Groningen. Hier zijn immers al cavernes aanwezig en is het CAES-concept al meer vertrouwd vanwege de min of meer vergelijkbare ontwikkelingen van de aardgas- en stikstof opslagen in zoutkoepels in respectievelijk Zuidwending en Heiligerlee. In het rapport wordt de veronderstelling uitgesproken dat (hierdoor) de vergunningprocedure voor een CAES in Groningen sneller zal verlopen. De zoutkoepel van Hooghalen zal eerst nader moeten worden onderzocht en er zullen een of meerdere cavernes moeten worden uitgeloogd. Er is wel enig voordeel van een 'op maat te maken' caverne en een aantal logistieke en infrastructurele aspecten van Hooghalen, maar deze zijn niet doorslaggevend. Wanneer aan de economische randvoorwaarden voor de ontwikkeling van een CAES in Noord-Nederland wordt voldaan valt echter nog niet te zeggen.

In de bijlage treft u ter informatie het rapport aan met daarin een management-samenvatting.

De resultaten van het onderzoek hebben (vooreerst) geen directe consequenties voor de burgers van de regio Hooghalen. Echter, gezien de maatschappelijke relevantie en mogelijke gevoeligheid van het thema 'diepe ondergrond' en alles wat daar mogelijk kan plaatsvinden, is het van belang dat de gemeente Midden-Drenthe en de belangenvereniging Hooghalen ook geïnformeerd worden. De belangenvereniging Hooghalen heeft over de mogelijke bestemming van de zoutkoepel Hooghalen in 2010 al eens bij de provincie een aantal vragen neergelegd.
De gemeente en de belangenvereniging zullen schriftelijk geïnformeerd worden en krijgen tevens een kopie van het onderzoeksrapport.

Hoogachtend,

gedeputeerde staten van Drenthe,

, secretaris , voorzitter

Bijlage(n):
jk.coll

GCS 12.R.52924

CAES Pre-feasibility study

Groningen, June 6, 2012

Authors W. Sloterdijk, G. Timmers, G. Magneschi, P. Ploumen, V. Monsma, ,
D. van Hameren, T. Slot, J. Lindeman

auteur : Timmers		12-01-31	beoordeeld	: Sloterdijk	12-06-31
B	152 blz.	bijl.		goedgekeurd	: v. Elteren	12-06-31

KEMA Nederland B.V. Utrechtseweg 310, 6812 AR Arnhem Postbus 9035, 6800 ET Arnhem
T (026) 3 56 91 11 F (026) 3 89 24 77 contact@kema.com www.kema.com Handelsregister Arnhem 09080262

MANAGEMENT SAMENVATTING

Er is een haalbaarheidstudie uitgevoerd naar het ontwikkelen van een 300 MW Compressed Air Energy Storage (CAES) installatie die gebruik maakt van bestaande cavernes in de provincie Groningen of van een nieuw te ontwikkelen caverne, zoals die mogelijk in Drenthe gerealiseerd zou kunnen worden. De essentie van de installatie is dat het overtollige, goedkope elektrische energie gebruikt om perslucht op te slaan, die vervolgens in tijden van tekort als dure energie weer geleverd kan worden.

Hiertoe zijn verschillende **concepten** geëvalueerd. Het resultaat hiervan is weergeven in de bijgevoegde tabel (beoordelingscriteria van erg goed (++) tot erg slecht (--).

CAES Concept	Efficiency (%)	Simplicity	Flexibility	Maturity	Sustainability
Conventional	42	++	++	+	-
Recuperated	54	+	++	+	-
Recuperated Optimized	58	+	++	+	-
Adiabatic	70	-	-	--	+
Combined cycle	60-65	--	--	+/-	-
Steam injection	54-58	-	+/-	+/-	-
Humid air	54-58	+/-	+/-	+/-	-

In de uitgevoerde haalbaarheidstudie zijn belangrijkste keuzecriteria het rendement, de eenvoud van de installatie, de technische haalbaarheid en snelle inzetbaarheid. Op basis hiervan is gekozen voor het concept "CAES optimized recuperated cycle" met een overall rendement van 58%.

Meerdere reeds bestaande **cavernes** in de AkzoNobel caverne locatie Heiligerlee zijn potentieel geschikt voor CAES. Dit geldt ook voor een nieuw te ontwikkelen caverne in Heiligerlee, Zuidwending of elders, bijvoorbeeld in de zoutdome bij Hooghalen. De caverne moet aan stabiliteitscriteria voldoen, zoals zijn locatie in het caverne veld, de vorm, de maximaal en minimaal toelaatbare druk en maximale drukdaling per dag. Voor een 300 MW CAES installatie die 6 uur kan uitzenden is een caverne nodig met een grootte van ca. 600000 m3 watervolume. Vanwege de hoge send-in en send-out capaciteit is er een nieuwe ondergrondse boring nodig voor zowel nieuwe als bestaande cavernes met een inwendige buis diameter van ca 350 mm doorsnede. Om bodemdaling gegarandeerd te kunnen beperken, wordt in deze studie ervan uitgegaan dat de cavernes bedreven worden op een hoge druk, ca 80 tot 90 % van de gesteentedruk op de diepte van de caverne. Daarnaast wordt uitgegaan van de geaccepteerde drukdaling van maximaal 10 bar/dag.
Voor bestaande cavernes in Heiligerlee is daarom gekozen voor een hoge bedrijfsdruk van 108 bar. Hierop is de bovengrondse **installatie** aangepast en als locatie hiervoor is Zuidbroek

gekozen. Het berekende overall rendement voor deze installatie is 58%. De slaagkans voor het verkrijgen van de vergunningen wordt op meer dan 90% geschat. CAES in Heiligerlee zou sterk lijken op de stikstofbuffer, die momenteel wordt gerealiseerd. Als doorlooptijd van de benodigde MER met vergunningen moet met een periode van 2 jaar worden gerekend.
Voor nieuw te ontwikkelen cavernes is een locatie in Drenthe, in de zoutkoepel van Hooghalen uitgewerkt voor een bedrijfsdruk van 75 bar. Hierop is de bovengrondse installatie aangepast en hiervoor is een locatie iets westelijk van Hooghalen gekozen. Het berekende overall rendement voor deze installatie is 59%. De slaagkans voor het verkrijgen van de vergunningen is moeilijk in te schatten omdat het een 'greenfield' ontwikkeling betreft, waarin ook bestemmingsplannen e.d. moeten worden gewijzigd. Als doorlooptijd voor het verkrijgen van de benodigde vergunningen, inclusief een MER, moet met een periode van 3,5 jaar rekening jaar worden gehouden.

De **investeringskosten** zijn specifiek gemaakt voor de aangegeven locaties, inclusief alle aansluitingen. De gemiddelde investering voor een CAES faciliteit voor Heiligerlee wordt geschat op 280 miljoen € (932 €/kW) en voor een nieuwe caverne op en nieuwe locatie bij Hooghalen 341 miljoen € (1135 €/kW). Mocht een nieuwe ca 70 bar caverne worden ontwikkeld op een locatie waar al een zoutinfrastructuur aanwezig is, dan is de investering ca 240 miljoen € (ca. 800 €/kW) en is daarmee in dezelfde ordegrootte als de investering voor een combined cycle gasturbine centrale.

Om de totale **business case** te maken, is nagegaan of deze investering rendabel is te maken in het licht van verwachte prijsontwikkelingen in de Europese energie markt. De opbrengsten van CAES moeten komen uit het op de spot markt goedkoop inkopen (bijvoorbeeld in de nacht) en het duur verkopen (gedurende de dag) en door het balanceren van de elektriciteitsvraag en aanbod in een bepaalde regio. Hiertoe zijn 3 scenario's geëvalueerd met het simulatie programma Plexos, te weten: Business-as-usual, Nucleair moratorium en Duurzame ontwikkeling. De gegevens die hieruit komen worden gecombineerd met de benodigde investeringen om te komen tot een Netto Contante Waarde (NCW) berekening. Voor de scenario's Business-as-usual en Nucleair moratorium worden NCW's berekend van 100den miljoenen Euro's negatief. Alleen voor het duurzame scenario wordt een positieve NCW berekend. Hierbij moet worden aangetekend dat Plexos voor de duurzame ontwikkeling na 2035 vanwege blijvende subsidiering op productie (kWh-basis) negatieve elektriciteitsprijzen voorspelt en hiermee wordt het resultaat van deze analyse twijfelachtig. De simulaties tonen overigens duidelijk aan dat enkel inkomsten, gegenereerd door handelen op de spot markt, onvoldoende lonen. Een deel van de inkomsten moet ook komen uit de reservemarkt, via balanceren van de elektriciteitsvraag.

De **visie** op basis van het huidige inzicht is, dat dagelijkse fluctuaties in de elektriciteitsprijs van minimaal 25 €/MWh gedurende enkele uren per dag nodig zijn om een acceptabele business case te verkrijgen.
CAES is gezien dit onderzoek met name geschikt voor het opvangen van elektrische energie in geval van negatieve elektriciteitsprijzen, wat kan optreden bij sterke groei van (offshore) wind en

instandhouding van de huidige subsidiering van windenergie. Door deze subsidiering draait wind door bij negatieve marktprijzen en kan CAES toch rendabel zijn, ongeacht het gekozen marktscenario.
Daarbij is vooral Adiabatische CAES, als dat is tot voldoend volwassenheid is ontwikkeld, een sterk scenario, omdat er dan op het moment van hoge energieprijzen geen duur aardgas meer hoeft toegevoerd te worden voor elektriciteitsproductie en vanwege het hoge rendement.
Adiabatische CAES maakt, anders dan de andere concepten, gebruik van opslag van de hitte van de uitlaatlucht van de compressoren.

EXECUTIVE SUMMARY

A feasibility study into developing a 300 MW Compressed Air Energy Storage (CAES) system, that uses existing caverns in the province of Groningen or with a new cavern, as could for instance be developed in Drenthe, has been performed. The essence of the installation is that it uses excess cheap electrical energy to store compressed air, which then, in times of shortage, will be used for the supply of expensive electrical energy.

Different **concepts** are evaluated. The result is displayed in the attached table (evaluation of very good (++) to very bad (--).

CAES Concept	Efficiency (%)	Simplicity	Flexibility	Maturity	Sustainability
Conventional	42	++	++	+	-
Recuperated	54	+	++	+	-
Recuperated Optimized	58	+	++	+	-
Adiabatic	70	-	-	--	+
Combined cycle	60-65	--	--	+/-	-
Steam injection	54-58	-	+/-	+/-	-
Humid air	54-58	+/-	+/-	+/-	-

In the performed feasibility study important selection criteria are: efficiency, simplicity of installation, the technical feasibility (maturity) and short start-up time. Based on this, the concept "CAES optimized recuperated cycle" with an overall yield of 58% has been selected.

Several existing **caverns** in the Akzo Nobel cavern location Heiligerlee are potentially suitable for CAES. This also holds for a new to develop cavern in Heiligerlee, Zuidwending or elsewhere, for example in the salt dome at Hooghalen. The cavern must meet stability criteria, such as its location in the cavern field, the form, the maximum and minimum pressure and maximum allowable pressure drop per day. For a 300 MW CAES plant with 6 hour send-out capacity a cavern system with a size of approximately 600,000 m3 of water volume is needed. Because of the required high send-in and send-out capacity, a new drilling, with an internal tube diameter of about 350 mm diameter, is required for both new and existing caverns. To guarantee limitation of subsidence, this study assumes that the caverns are operated at high pressure, about 80 to 90% of the rock pressure at the depth of the cavern. Furthermore, the accepted pressure drop of up to 10 bar / day has been taken for granted.
For existing caverns in Heiligerlee therefore, a high operating pressure of 108 bar has been set. This is used to design the aboveground **installation** and as location Zuidbroek is chosen. The calculated overall efficiency of this CAES plant is 58%. The success rate for obtaining the permits is estimated at more than 90%. CAES in Heiligerlee would closely resemble the nitrogen buffer, which is currently being realized. The required duration of obtaining the permits, including

Environmental Impact permits (MER) is estimated at 2 years.
For development of new caverns, a site in Drenthe, in the salt dome Hooghalen is worked out for an operating pressure of 75 bar. This is used to design the aboveground installation at a location slightly west of Hooghalen. The calculated overall efficiency for this CAES plant is 59%. The success rate for obtaining the permits is difficult to estimate because it is a greenfield development, which includes also the change of zoning plans etc. The time for obtaining the necessary permits, including an 'MER', is estimated at a period of 3.5 years.

Investment costs are made for the indicated locations, including all connections. The average investment (capex) for a CAES facility in Heiligerlee is estimated at 280 million € (932 €/kW) and for a CAES facility at a new cavern location in Hooghalen at 341 million (€ 1135/kW). If a new ca 70 bar cavern will be developed in a location where a salt infrastructure is present, then the investment is approximately 240 million € (800 € kW). This is of the same order of magnitude as the investment for a combined cycle gas turbine plant.

For the overall **business case** it is checked whether this investment is profitable in light of expected price developments in the European energy market. The revenues of CAES must come from cheap purchase at the spot market (for instance at night) and expensive sale (during the day) and by balancing electricity supply-and-demand in a given region. 3 scenarios are evaluated with simulation program Plexos, being: Business-as-usual, Nuclear moratorium and Sustainable Development. The calculated revenues will be combined with the investments in order to calculate Net Present Value (NPV). For scenarios Business-as-usual and Nuclear moratorium very negative NPV's (100 millions of Euro's negative) are obtained. Only for the sustainable scenario, a positive NPV is calculated. It should be noted that Plexos predicts negative electricity prices after 2035 for sustainable development, because of continued subsidies on production (kWh basis), making the result of this analysis questionable. The simulations show clearly that revenues, generated by only trading in the spot market, are inadequate. A portion of the income must also come from the reserve market through balancing the demand for electricity.

Future outlook based on current understanding is that daily fluctuations in the electricity price of at least 25 €/MWh for several hours per day, is necessary to obtain an acceptable business case. CAES is, based on the results of this study, particularly suitable for absorbing electrical energy in case of negative electricity prices, which can occur with strong growth of (offshore) wind energy development and conservation of the current subsidization of wind energy. Through this subsidizing, wind energy will still be produced at periods of negative market prices and CAES can be profitable, regardless the market scenario.
Especially Adiabatic CAES, if developed to maturity, is a strong scenario because at the time of electricity production at high energy prices, no additional expensive natural gas is needed electricity and also because of the high efficiency. Adiabatic CAES, unlike the other concepts, uses storage of the heat of the exhaust air from the compressors.

TABLE OF CONTENTS

1 ABBREVIATONS

CAES	Compressed air energy storage
CAPEX	Capital expenditure
CSP	Concentrating solar panels
DOE	Department of energy
GT	Gas turbine
HRSG	Heat recovery steam generator
OPEX	Operational expenditure

2 CAES TECHNOLOGY

In a CAES plant, electricity is used to compress air during off-peak hours when low-cost generating capacity is available or non dispatchable electricity is produced from intermittent sources such as wind turbines, solar panels or tide energy systems. Electricity is stored in the form of compressed air in underground or aboveground reservoirs and it is reused during peak hours when the demand and the electricity price is higher. Electricity can be in fact produced again by running an air expander with the pressurized air stored in the reservoir. Given the availability of pressurized air, it is usually more economical to increase plant output by using the air in a gas turbine instead of a simple air expander. The profit of operating a CAES plant is given by the difference between the cost of the electricity during off-peak hours and selling price during peak hours.

Therefore a CAES plant is operated alternatively in two modes:

1 *Storage mode (also charging mode)*: the low cost off-peak electricity from the grid is used to operate the motor-driven compressor to store the pressurized air into an underground storage facility
2 *Generation mode (also discharging mode)*: the compressed air is withdrawn from the storage reservoir and then expanded through a simple expander or a gas turbine to drive the generator providing peak power to the grid.

The round-trip efficiency, also called turn-around efficiency, of a CAES plant is defined as the ratio between the energy produced during generation mode and the energy consumed during storage mode within the time frame of a complete charge/discharge cycle (e.g. 24 hours).
Round-trip efficiency indicates the ratio between the electricity that is sent to the network over the sum of the electricity used in compressor during injection and the energy added with the fuel. The efficiency is calculated accounting the hours of injection and production during an entire cycle, thereof is defined as "round-trip".

Round trip efficiency is calculated as follow:
$\eta_{roundtrip} = MWe_{generator} \times h_{production} / (MWe_{compressor} \times h_{injection} + MWth_{fuel} \times h_{production})$

A conventional CAES plant cycle uses a gas turbine that includes a heat regenerator (as illustrated in Figure 2-2). The major components are:

- a motor/generator with clutches on both ends (to engage/disengage it to/from the compressor train, the expander train, or both)
- multi-stage air compressors with intercoolers to reduce the power requirements needed during the compression cycle, and with an after-cooler to reduce the storage volume requirements
- an expander (or gas turbine) consisting of high- and low-pressure turbo-expanders with combustors between stages

- control system (to regulate and control the off-peak energy storage and peak power supply, to switch from the compressed air storage mode to the electric power generation mode)
- auxiliary equipment (fuel storage and handling, cooling system, mechanical systems, electrical systems, heat exchangers)
- underground or aboveground reservoirs, including piping and fittings.

While combustion turbines are standardized power plant equipment, CAES plants are optimized for specific site conditions such as the availability and price of off-peak energy, cost of fuel, storage type (and the local geology if underground storage is used), load management requirements, peaking power requirements and capital cost of the facility.

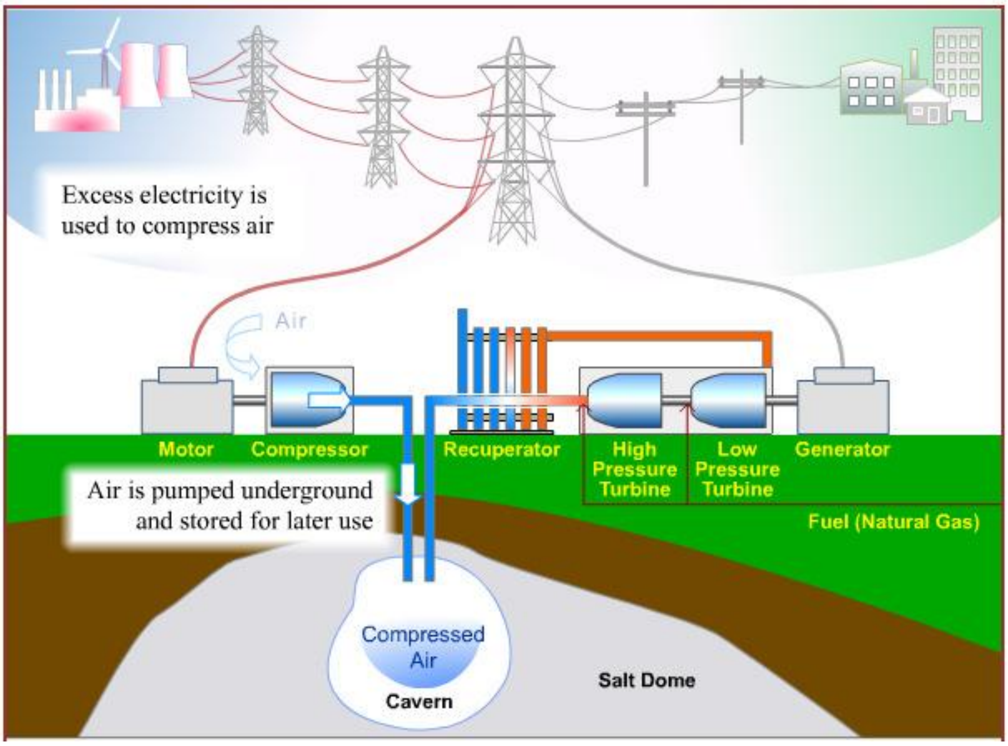


Figure 2-1 scheme of a recuperated CAES plant (storage mode)

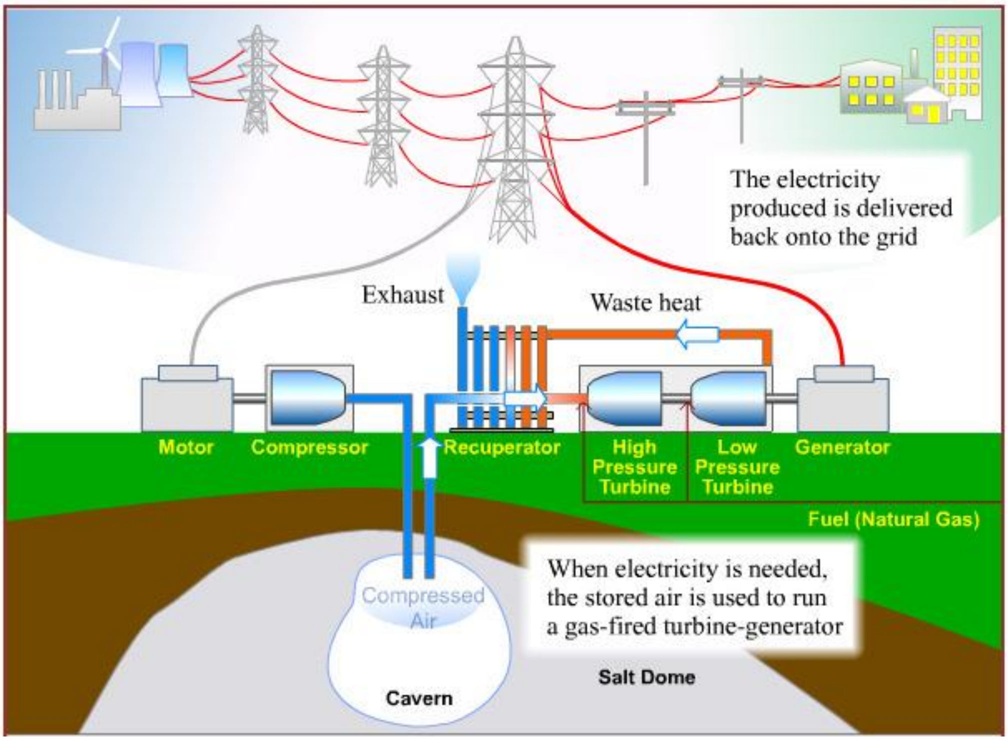


Figure 2-2 scheme of a recuperated CAES plant (generation mode)

Since the CAES plants use a fuel during the air discharge generation cycle, a CAES plant is not truly a “pure” energy storage plant such as pumped hydro, battery, and flywheel storage systems. In general, since fuel is used during a CAES plant’s generation cycle, a CAES plant provides approximately 25-60% more energy to the grid during on-peak times than it uses for compression during off-peak times. In addition the power output of an expansion turbine used in a CAES plant provides 2 to 3 time more power to the grid than the same expansion turbine would provide to the grid if it were a part of a simple-cycle combustion turbine plant. This explains the exceptionally low specific fuel consumption (heat rate) of a CAES plant as compared to a combustion turbine. For example, if the expansion turbine element from a 100-MW_e simple cycle combustion turbine were used in a CAES plant configuration, it would provide roughly 250 MW_e to the grid [Knoke 2002].

The advantage of including a CAES plant in the electricity generation and transmission network can be summarized in three points:

1 absorbing power generated by intermittent sources that cannot be dispatched on the grid,
2 creating additional electricity demand during low demand hours to keep base load generation plant running
3 acting as fast response emergency reserve.

2.1 Existing CAES plants

2.1.1 **Huntorf (GE)**

The Huntorf plant (Figure 2-4 & Figure 2-4 Huntorf CAES plant [Bullough 2004]) is the first compressed air storage power station in the world; it began commercial operation December 1978. Today, E.ON Kraftwerke of Bremen, Germany owns the 290-MW_e CAES plant in Huntorf, Germany. ABB was the main contractor for the plant. The compressed air is stored in two salt caverns between 640 and 790 meters below the surface with a total volume of 0.3 million cubic meters. The caverns have a maximum diameter of about 61 m and a height of 152 m. The cavern air pressure ranges from 43 to 70 bar. At the compressor airflow rate of 108 kg/s, the plant requires 12 hours for full recharge. At full power, the turbine draws 417 kg/s of airflow from the caverns for up to 4 hours. After that, the cavern pressure is too low to allow generation at 290 MW_e and the airflow supplied by the caverns decreases (although the plant will produce power at an exponentially declining power level for over 10 more hours). [Knoke 2002]

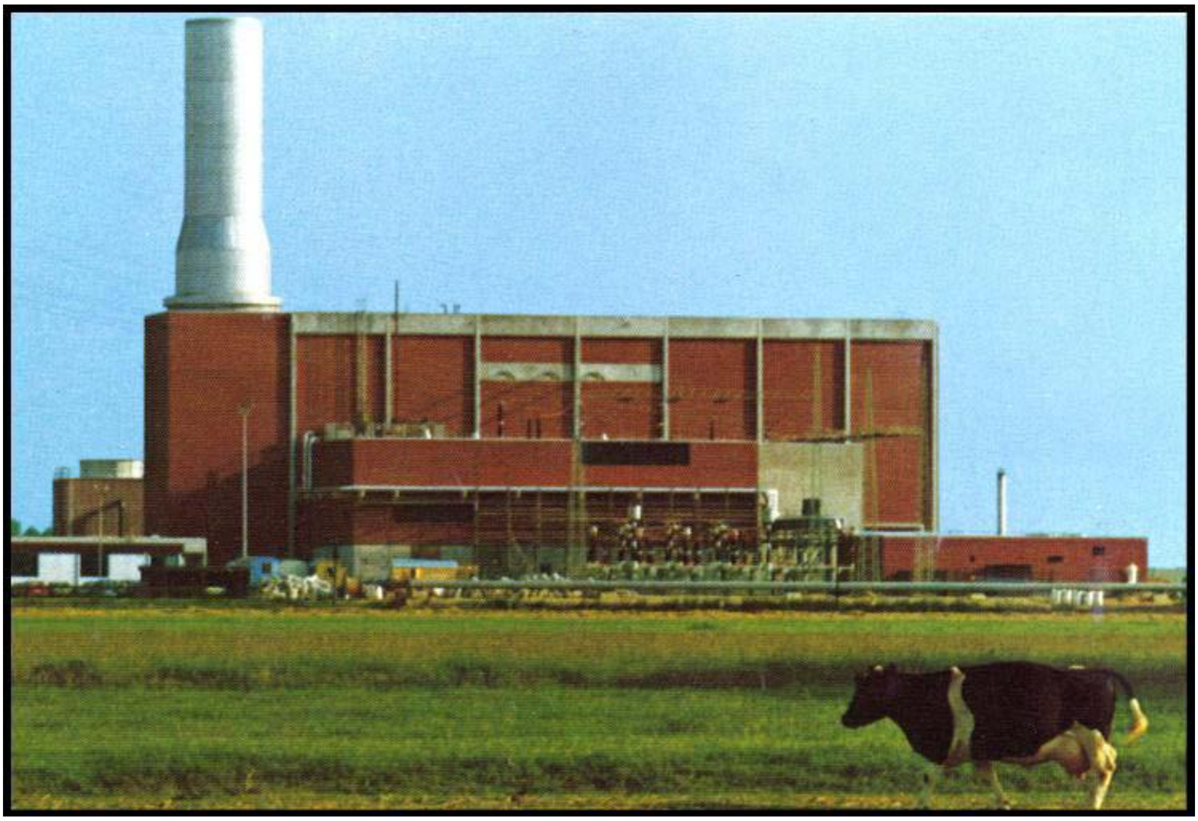


Figure 2-3 Huntorf CAES plant [Knoke 2002]

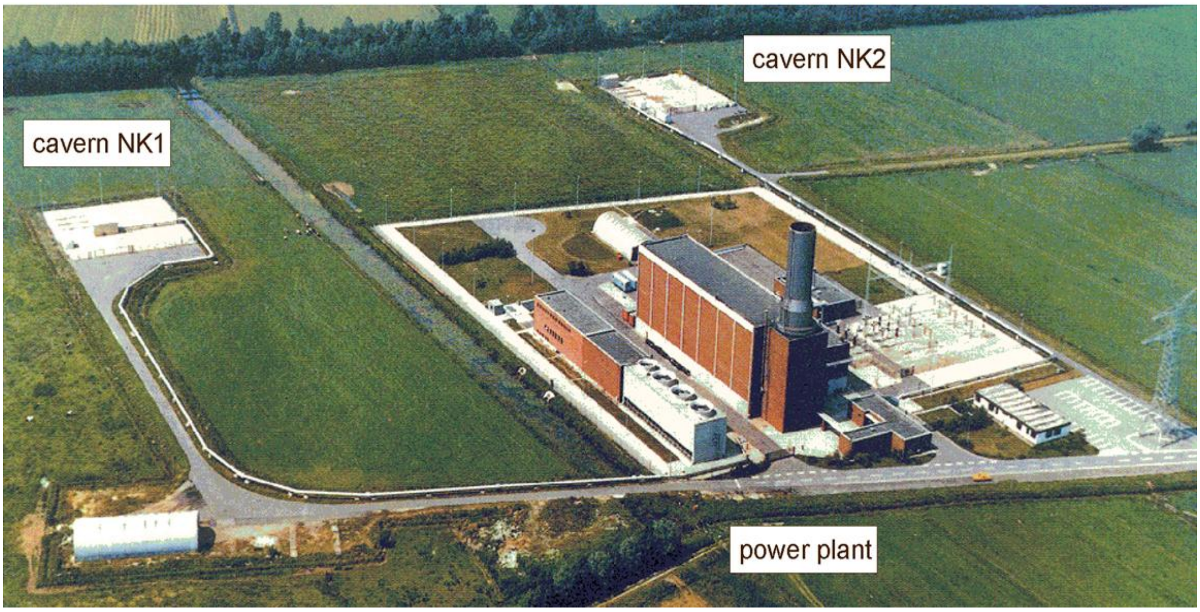


Figure 2-4 Huntorf CAES plant [Bullough 2004]

2.1.2 McIntosh (TX, US)

The 110-MW_e McIntosh plant (Figure 2-5), owned by the Alabama Electric Cooperative, is the second CAES power plant in the world, and the first in the United States. Dresser-Rand designed and constructed the entire turbo-machinery train. The overall plant (turbo-machinery, building, and underground cavern) was constructed in 30 months for a cost $51 million (1991 dollars) and was completed on June 1991. The air is compressed in three stages, each followed by an intercooler. The compressed air is stored in a salt cavern between 460 and 760 m below the surface with a total volume of 0.54 million cubic meters, yielding a power generating duration of 26 hours at full power and at 340 lb/s. The cavern air pressure ranges from 45 to 75 bar during normal operation. The reheat turboexpander train has high- and low-pressure expanders with high and low pressure combustors and drives the electric motor/generator to produce peak electric power. Dual-fuel combustors are capable of burning natural gas or fuel oil. An advanced regenerator is used to extract thermal energy from the low-pressure expander exhaust to preheat inlet air from the storage cavern before it goes to the inlet of the high-pressure combustor. The regenerator reduces fuel consumption by approximately 25%. [Knoke 2002]

Figure 2-5 McIntosh CAES plant [PE, 2011]

3 REVIEW OF CAES CONCEPTS

This chapter presents an overview of several CAES concepts which are suitable for the Groningen and Drenthe regions where the potential for CAES application in salt caverns exists. The objective of this review is to describe the different concepts and to make a benchmark of them, in order to ultimately select the most suitable concept.

The following CAES concepts will be discussed in this chapter:

- CAES conventional cycle
- CAES recuperated cycle
- CAES recuperated optimized cycle
- CAES adiabatic cycle
- CAES combined cycle
- CAES steam injection cycle
- CAES humid air cycle.

Additional options for CAES plants and more innovative concepts are presented for information in APPENDIX I. These options mentioned are not included in the selection because they are not mature enough (their advantages have to be demonstrated in practice) or because they were not suitable for the considered locations.

3.1 Ranking criteria's

The selection of the CAES concept for further techno/economical evaluation has been conducted using these criteria as guidelines:

- *Simplicity*: CAES being a relatively new type of application, simple configurations with limited number of components are preferred in order to reduce the complexity in operation and control, and also the risk of failure.
- *Flexibility*: one of the advantages of CAES is the flexibility, namely the fast response to variation during operation (start up and partial loads). The faster the start-up and the ramp rate are, the more chances the plant has to operate. Some configurations include components that act as a bottleneck during the start-up or load variations (e.g. heat storage).
- *Maturity*: CAES maturity is quite low for most of the concepts since only two plants have been built so far. Although CAES plants can be built from existing technologies, this is a new field of application were technologies need to be adapted to the specific plant purpose and characteristics, therefore requiring additional developments and verifications.
- *Round-Trip Efficiency:* efficiency is a key indicator since the operational cost and the environmental impact of the plant strictly depend on this parameter.

– *Sustainability:* the use of fuel reduces the sustainability of the plant due to the associated emission (of pollutants and CO_2) and consumption of fossil fuel. The lower the gas consumption, the more sustainable the plant is. Water demand for cooling or for the process itself (e.g. steam injection) also reduces the sustainability of this application.

For the key indicator round-trip efficiency the figures are in numbers. For the other ranking criteria this exact information is not available and the ranking is qualitative and made by assigning, for each criteria, an index that is defined as follow:

++ = very high
+ = high
+/- = medium
- = low
-- = very low

Each concept reviewed in this chapter has been benchmarked with the criteria and the method described above. The aim of the benchmarking is that of indicating which concept is the most attractive.

3.2 CAES conventional cycle

This is the simplest configuration for a CAES plant, also called first generation CAES. The round-trip efficiency of this plant is around 42% [Bieber 2010] and it is not optimal because the heat of the flue gas exiting is lost in the atmosphere instead of being used to pre-heat the cold air coming from the reservoir. The compressor is equipped with a certain number of inter-stage coolers therefore a cooling system is required. The Conventional CAES plant has a layout as illustrated in Figure 3.1. A CAES cycle arranged like this is not much different from an open cycle gas turbine plant – the major difference is that in this case the compressor is intercooled. Another difference is that the axis connecting compressor, generator and expander must be equipped with clutches to allow disconnection of compressor or expander. The expander is connected during production and during the charging period the compressor is connected and the generator functions as a motor. Such a configuration has been demonstrated in Huntorf. The maturity level of this concept is relatively high because it's made from existing technology and can be built by adapting existing commercial components.

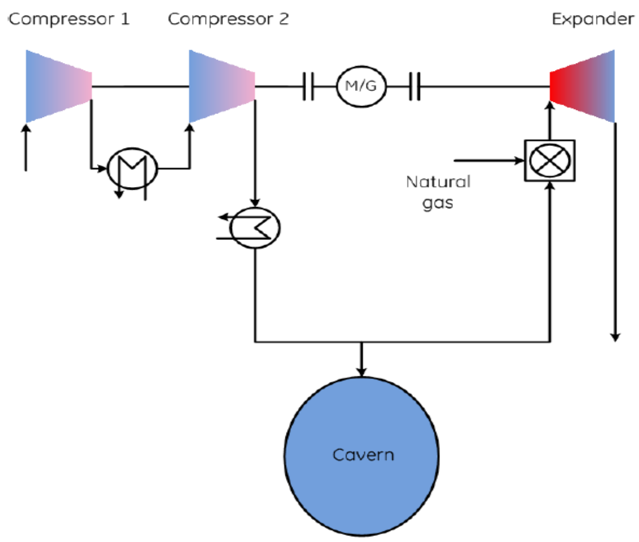


Figure 3-1 Scheme of CAES conventional cycle [Bieber 2010]

Figure 3.2 shows the detail of the gas turbine configuration, that is split in two stages each with is own burner.

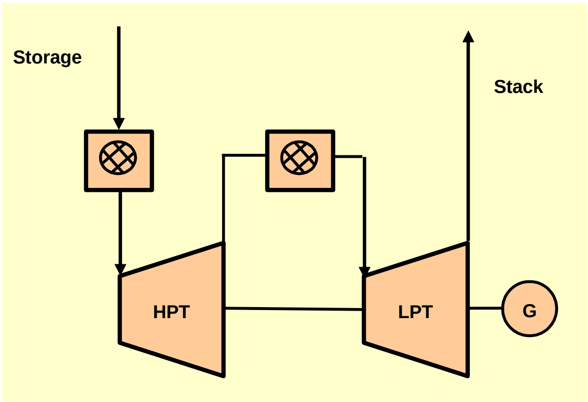


Figure 3-2 Detail of the gas turbine configuration for conventional CAES

Table 3-1 Ranking of CAES conventional cycle

CAES conventional		
Index	Rank	Comment
Simplicity	++	Simple layout and limited number of components
Flexibility	++	Fast start-up of expander allows high flexibility in operation
Maturity	+	Derived from existing technology; concept already demonstrated (Huntorf)
Efficiency	--	It is the least efficient CAES concept (42% [Bieber 2010])
Sustainability	-	Uses fuels and produces local emission

3.3 CAES recuperated cycle

The recuperated cycle CAES is also one of the simpler concepts, called second generation CAES. The round-trip efficiency is around 54% [Bieber 2010], more efficient in comparison to the conventional CAES. The recuperated CAES plant has a layout as illustrated in Figure 3-3. Efficiency is higher because heat from the exhaust gas is recovered in the process by pre-heating the cold air before the burner in the regenerator. The compressor is equipped with a certain number of inter-stage coolers that are served by a cooling system.

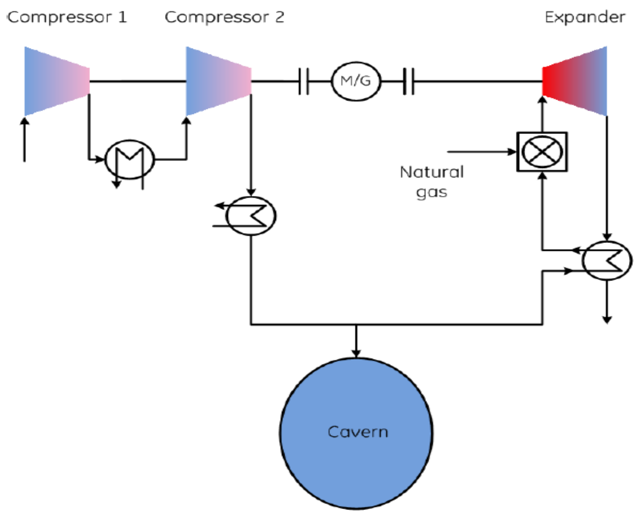


Figure 3-3 Scheme of CAES recuperated cycle [Bieber 2010]

This plant layout is similar to the conventional one, thus is relatively simple. In this case an additional heat exchanger (regenerator) must be installed downstream the expander turbine to recover the heat from the exhaust gas. Figure 3-2 shows the detail of the gas turbine configuration, that is split in two stages each one with is own burner. This configuration includes the regenerator.

This plant configuration has been demonstrated in McIntosh. The maturity level of this concept is relatively high because it's made from existing technology and can be built by adapting existing commercial components.

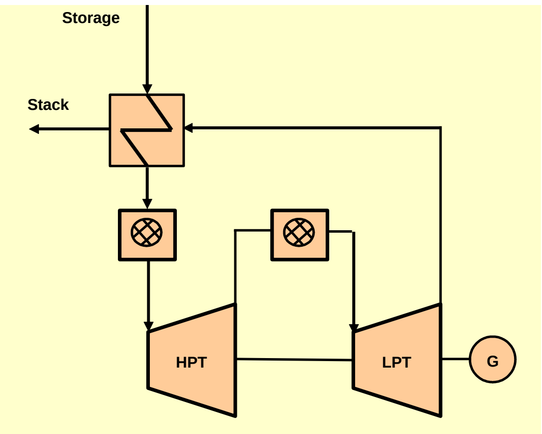


Figure 3-4 Detail of the gas turbine configuration for recuperated CAES

Table 3-2 Ranking of CAES recuperated cycle

CAES recuperated		
Index	Rank	Comment
Simplicity	+	Simple layout and limited number of components, some additional complexity because presence of regenerator
Flexibility	++	Fast start-up of expander allows flexibility in operation
Maturity	+	Derived from existing technology; concept already demonstrated (McIntosh)
Efficiency	+/-	Improved efficiency with respect to conventional CAES thanks to the regenerator (54% [Bieber 2010])
Sustainability	-	Uses fuels and produces local emission

3.4 CAES optimized recuperated cycle

The optimized recuperated cycle is similar to the recuperated cycle described before since it uses the same plant layout including a regenerator. The main difference lies in the positions of the burner (see Figure 3-5) that is placed at the exit of the low pressure expander, before the regenerator. Such configuration is described in [Tuschy 2004] and allows a gain in efficiency, although limited, because the fuel can be injected in the burner at lower pressure saving energy to compress or pump the fuel.

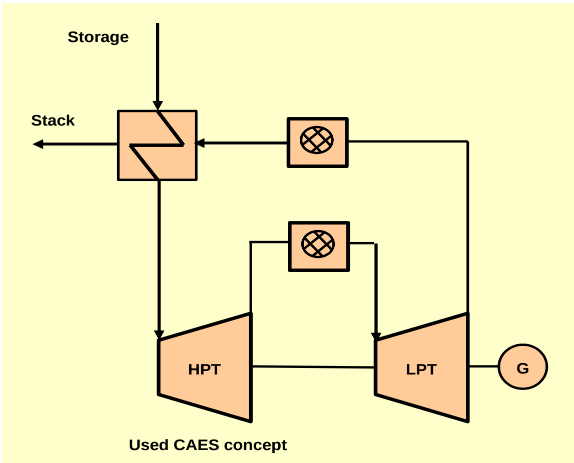


Figure 3-5 Detail of the gas turbine configuration for optimized CAES

For this concept KEMA estimates a round-trip efficiency of approximately 58% (see chapter 6), higher than the recuperated concept (McIntosh). Improvements of the efficiency are not due only to the different burner position but also by different operating parameters chosen in the KEMA design (i.e. higher expander inlet temperatures).

Similarly to the McIntosh plant, this plant can also be realized starting from existing equipment by adapting them to the special design of this configuration. The concept has overall the same level of maturity of the recuperated CAES although the type of turbo-machinery needs some adaptations. A general remark has to be made that at present moment development resources for CAES application have been downsized.

Table 3-3 Ranking of CAES optimized recuperated cycle

CAES optimized recuperated		
Index	Rank	Comment
Simplicity	+	Simple layout and limited number of components, little additional complexity because presence of regenerator
Flexibility	++	Fast start-up of expander increase flexibility in operation
Maturity	+	Derived from existing technology; concept similar to the existing McIntosh plant.
Efficiency	+	Improved efficiency with respect to recuperated CAES (58% KEMA estimation)
Sustainability	-	Uses fuels and produces local emission

3.5 CAES adiabatic cycle

If the compressor is not equipped with intercoolers, the air at the compressor outlet can reach relatively high temperatures: in the order of 600 °C for a final pressure of 100 bar. In this case the heat of the hot air can be stored in a heat storage facility. It can than be reused during expander operation to heat up the air coming from the reservoir, in place of using fuel. This concept is called adiabatic because, when looking at the overall system, the process happens with (ideally) no heat exchange with the surroundings. In this concept the cooling systems for the intercoolers is almost eliminated (a limited intercooling is still applied), but instead a large heat storage facility has to be included. A schematic layout of Adiabatic CAES is illustrated in Figure 3-6.

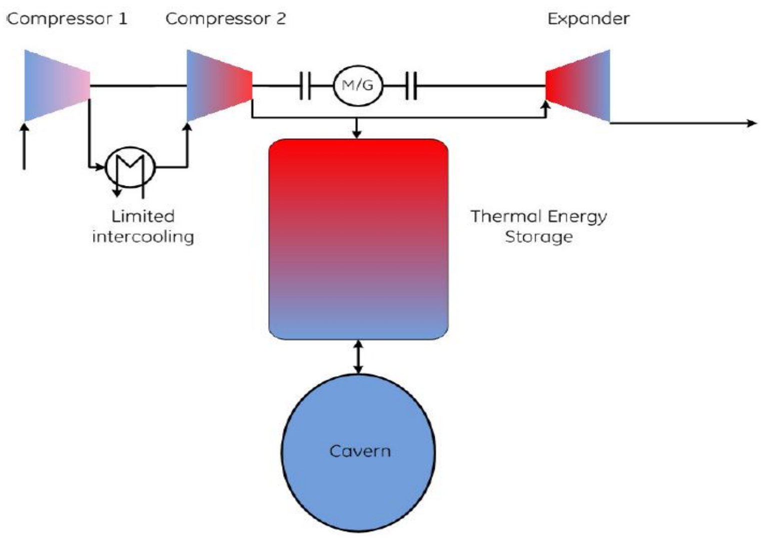


Figure 3-6 Scheme of CAES adiabatic cycle [Bieber 2010]

The theoretical round-trip efficiency of this system is around 70% [Bieber 2011], that is higher than the recuperated optimized CAES. This is due to the fact that in the adiabatic cycle almost all the heat released during compression is re-used in the expander and not lost to the environment by means of intercooling. In other words, the external fuel input is replaced by using the heat produced during compression. The fact that compression and expansion takes place in different moments of the day makes necessary to include a heat storage system. This concept has therefore the advantage of minimizing, or even eliminating, the fuel consumption and the related emissions. The disadvantage is that the thermal storage increases complexity and CAPEX of the plant and reduces the operational flexibility.

This concept is under study at the moment in the EU project "AA-CAES". A demo plant is in preparation and is part of the ADELE project leaded by RWE [Bieber 2011]. More details on the Adiabatic CAES concept are reported in Chapter 10 of this document.

Table 3-4 Ranking of CAES adiabatic cycle

CAES adiabatic cycle		
Index	Rank	Reason
Simplicity	-	Added complexity because the presence of heat storage
Flexibility	-	Heat storage inertia reduces flexibility in operation
Maturity	--	Concept under development and still to be demonstrated.
Efficiency	++	The highest (70% theoretical) efficiency amongst CAES concepts
Sustainability	+	Very little fuel use and local emissions to atmosphere

3.6 CAES combined cycle

Another way to increase the efficiency of a CAES plant, with respect to the first generation CAES is that of using a combined cycle. The hot flue gas exiting the expander is used as feed for a Heat Recovery Steam Generator (HRSG).The round trip efficiency of CAES combined cycle is estimated to be approximately 60-65% that is higher than the efficiency of conventional combined cycle (58-60%) because the intercooled compression. The disadvantage is that the installation cost (CAPEX) The hot flue gas exiting the expander can also be used and the complexity of this system increase significantly. Moreover the start up time of this system is longer than the conventional or recuperated CAES. It takes approximately one hour to reach full capacity after start up, reducing the ability of the plant to act as fast response generation plant. A schematic layout of Combined Cycle CAES is illustrated in Figure 3-7. A configuration with single generator for the expander and the ST could allow more flexibility and faster startup of the plant, although at increased cost.

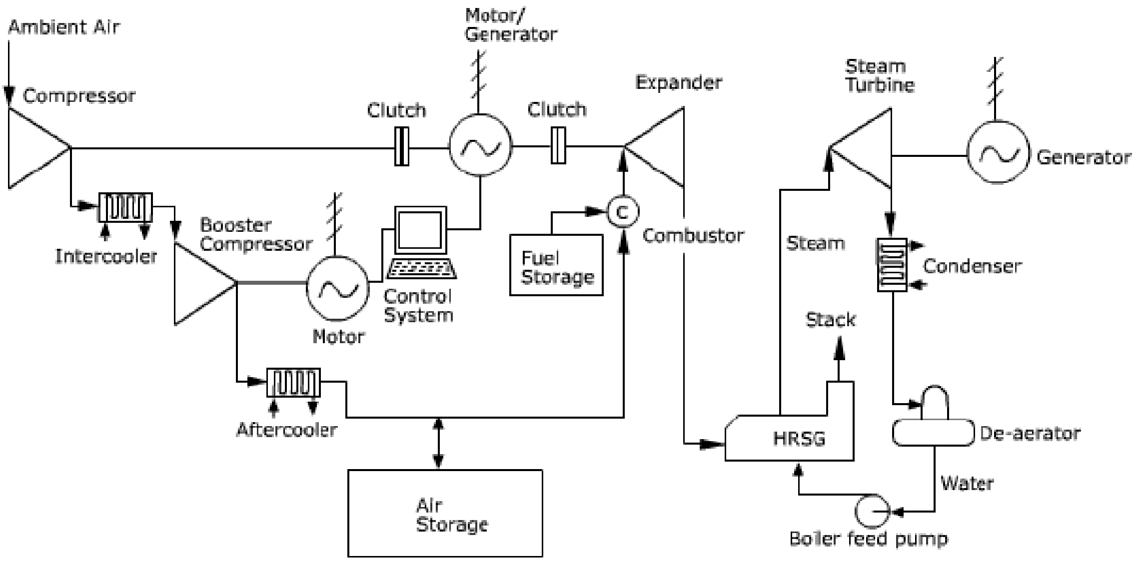


Figure 3-7 Scheme of CAES combined cycle [Knoke 2002]

The level of maturity is high because most of the components are derivable from existing commercial technologies; however this specific type of concept has been never demonstrated for CAES applications, thus with respect to conventional or recuperated concept the maturity of this concept is slightly lower.

Table 3-5 Ranking of CAES combined cycle

CAES combined cycle		
Index	Rank	Reason
Simplicity	--	Complex layout because the presence of steam cycle
Flexibility	--	Steam cycle inertia and increased number of components limits the flexibility in operation
Maturity	+/-	Near-commercial equipment but no similar application has never

		been demonstrated for CAES purposes
Efficiency	++	Predicted efficiency of 60-65%
Sustainability	-	Fuel use and local emissions to atmosphere

3.7 CAES steam injected cycle

The hot flue gas exiting the expander can also be used to produce steam in a HRSG which is again injected into the compressed air stream before the inlet of the expander (after the burner). This is an alternative way of using the enthalpy of exhaust gases, in this case heat is reintroduced in the process by means of steam. A schematic layout of Steam Injected CAES is illustrated in Figure 3-7.

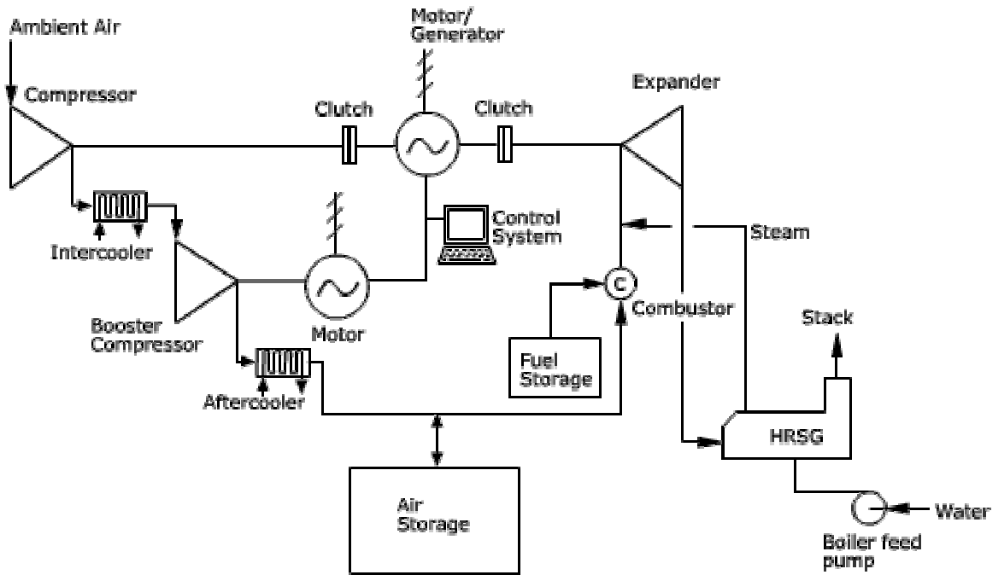


Figure 3-8 Scheme of CAES steam injection cycle [Knoke 2002]

The fuel consumption is reduced similarly to the recuperated CAES concept. In other words, this represents an alternative way to increase the round-trip efficiency with respect to the recuperated CAES. The disadvantage is that this system requires a certain amount of de-mineralized water, which introduces the need of water availability and additional consumption of energy for the de-mineralization plant. This configuration results in a round-trip efficiency that is similar to the recuperated CAES, because they use a similar solution for recuperating energy from exhaust gas. A portion of the efficiency improvement will be, however, canceled out by the additional power consumption of the de-mineralization plant.

Most of the components are derivable from existing commercial technologies; however this specific type of concept has been never demonstrated for CAES applications. Compared to the conventional or recuperated concept, the maturity of this concept is somewhat lower.

Table 3-6 Ranking of CAES steam injected cycle

CAES steam injected cycle		
Index	Rank	Reason
Simplicity	-	Simple layout and limited number of components, additional complexity because presence of steam generator and demi-water plant
Flexibility	+/-	Steam boiler inertia could slow down start up or load variations, but is not expected to be critical
Maturity	+/-	Near-commercial equipment but no similar application has been demonstrated for CAES purposes
Efficiency	+	Expected to be similar to recuperated CAES (54-58%)
Sustainability	-	Fossil fuel use and local emissions to atmosphere

3.8 CAES humid air cycle

The humid air cycle CAES configuration is similar to the steam injection cycle. However, instead of producing and injecting steam, the cold air is saturated with water. Water and air are both pre-heated using heat of the exhaust gas. The saturation of the air stream takes place before the combustor, while steam injection takes place after the combustor. A schematic layout of Humid Air CAES is illustrated in Figure 3-9.

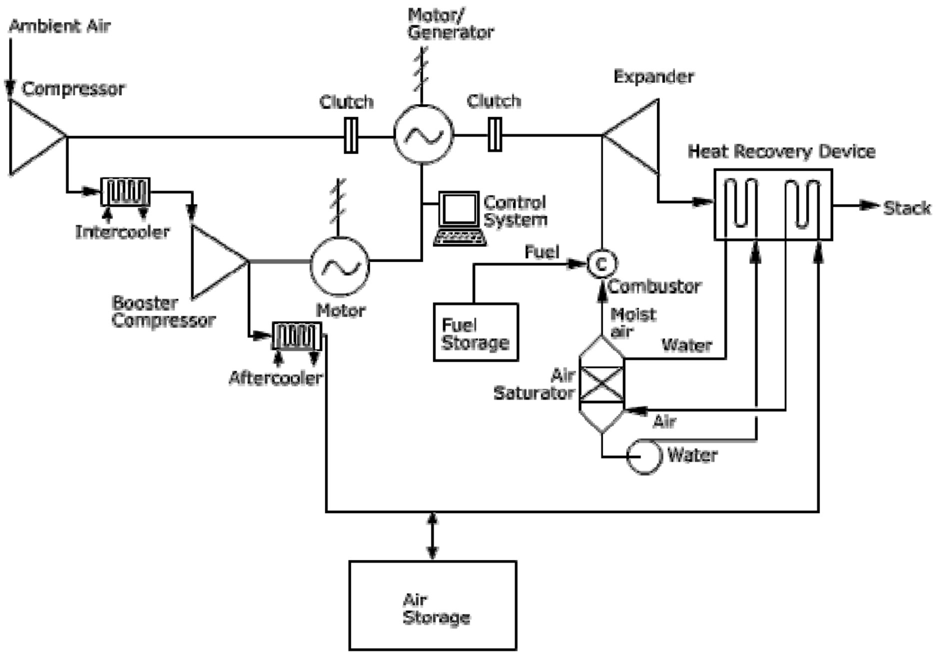


Figure 3-9 Scheme of CAES Humid Air cycle [Knoke 2002]

A certain amount of water must be available at the plant site but it doesn't need to be de-mineralized water [Knoke 2002].

The round-trip efficiency of the plant is expected to be comparable to the recuperated CAES cycle since a similar recuperation system is applied (although using different means) Exact figures are not available but a slightly lower efficiency than the recuperated CAES is expected.

Most of the components are derivable from existing commercial technologies; however this specific type of concept has been never demonstrated for CAES applications, thus with respect to conventional or recuperated concept the maturity of this concept is lower.

Table 3-7 Ranking of CAES humid air cycle

CAES humid air cycle		
Index	Rank	Reason
Simplicity	+/-	Simple layout and limited number of components, additional complexity because presence of system for air humidification
Flexibility	+/-	Air saturator inertia could slow down start up or load variations, but is not expected to be critical
Maturity	+/-	Near commercially available but no similar application has never been demonstrated for CAES purposes
Efficiency	+	Expected to be similar to recuperated CAES (54-58%)
Sustainability	-	Fossil fuel use and local emissions to atmosphere

4 SELECTION OF CAES CONCEPT

In this chapter the selection of the CAES concept to be used in this study is discussed. The aim is to select one concept to be realized in the region of Groningen and Drenthe. In the region of Groningen salts cavern with adequate volume and pressure are available, in the region of Drenthe they can be created. Table 4-1 summarizes the technical ranking presented in the previous chapter for each concept.

Table 4-1 criteria's ranking for each concept

CAES Concept	Efficiency (%)	Simplicity	Flexibility	Maturity	Sustainability
Conventional	42	++	++	+	-
Recuperated	54	+	++	+	-
Recuperated Optimized	58	+	++	+	-
Adiabatic	70	-	-	--	+
Combined cycle	60-65	--	--	+/-	-
Steam injection	54-58	-	+/-	+/-	-
Humid air	54-58	+/-	+/-	+/-	-

Legend: ++ Very high, + High, +/- Medium, - Low, -- Very Low

The "optimized recuperated CAES" has been selected as the most suitable plant concept considering the scopes of this study. Efficiency is high and only the immature adiabatic cycle CAES concept has a significant higher efficiency. This immaturity makes it at this moment impossible to select this concept for a (pre)feasibility study. The combined cycle CAES concept has a higher efficiency, but is very complex, expensive and inflexible and for this moment not an optimum choice. Possibly an extension of the now chosen recuperated optimized cycle CAES to a combined cycle is for later consideration.

All the criteria's ranking show in fact that the optimized recuperated CAES is the one which satisfies most criteria High flexibility is critical because allows the plant to enter in operation in short time. This is a required characteristic of a CAES plant; the higher the flexibility the more chances the plant has to participate actively in the electricity grid. A high level of maturity is important to reduce the risk of investment and minimizes the chances of unexpected operational problems. The round-trip efficiency has to be high to reduce operation cost and fuel consumption.

The selection process aims towards an efficient concept that can be realized in near terms without extensive R&D and with a manageable project development risk. The very low level of maturity disqualifies the Adiabatic CAES design. The Conventional CAES has a too low round-trip efficiency to be viable on large scale. Of the remaining CAES concepts, the Recuperated Optimized CAES scores best on all criteria.

CAES plants already exist and are proven in concept, but there's still limited experience in this field. The risk associated with implementing never demonstrated innovative concepts is high. A more careful approach is suggested, that can reduce risk, costs and efforts. The Recuperated Optimized CAES concept combines this focus on reducing risk with a high flexibility and good efficiency.

On the other hand, KEMA believes that the current research could bring much innovation and especially demonstrate the feasibility of the most innovative concept, namely the adiabatic CAES. This concept represents a future potential option and it is suggested to consider it as a "secondary" option for future application in Groningen and Drenthe regions. The adiabatic CAES is interesting in particular because does not use any fuel and this introduces benefits related to environmental and permitting issues. On the other hand the economic feasibility of adiabatic CAES has to be carefully assessed due to the additional cost and complexity of the thermal storage. This option is the best choice for a medium term research project.

5 CAVERN SELECTION

5.1 Cavern selection criteria

A number of criteria determine the use of caverns for compressed air storage. These criteria are often given by the Staatstoezicht op de Mijnen and based on many years of experience in the Netherlands and Germany. In principle, it is possible to operate outside the boundary conditions, but such operation will have to be proven by extensive analysis and calculations. For this study, KEMA has chosen to use the existing criteria for cavern selection.

5.1.1 Cavern stability

Stability and integrity of the cavern are highly essential for safe business operations.

For this purpose specific cavern criteria are determined and have been assessed. During the examinations of the caverns information from AkzoNobel and directives from the German agency IfG from Leipzig has been used. The directives from IfG are also used by AkzoNobel and Gasunie during the gas storage project in Zuidwending and the nitrogen buffer in Heiligerlee and are acknowledged by SoDM.

5.1.2 Cavern distance to the sides of the salt-dome

The thickness of the salt from the side of the cavern until the side of the salt dome must be a minimum of 150 meter. This distance guarantees stability and integrity of the cavern (Figure 1, distance A).

5.1.3 Distance cavern roof to top of the salt-dome

The thickness of the salt from the upper side of the cavern until the top of the salt below the surface has to be a minimum of 200 meter. This distance guarantees stability and integrity of the cavern (Figure 1, distance B).

5.1.4 Distance between caverns

For gas storage the distance between caverns is advised to be at least 150 meter. This distance guarantees stability and integrity of the cavern (Figure 1, distance C).

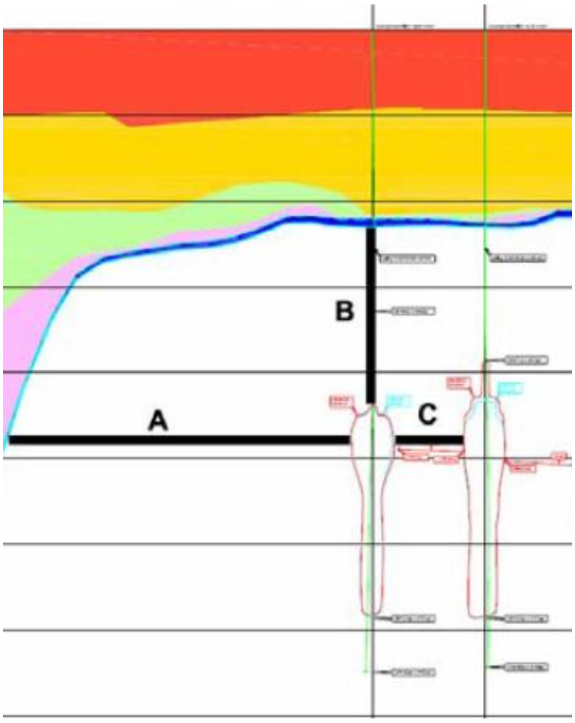


Figure 1 Rock-mechanic relevant distances

5.1.5 **Maximum cavern pressure**

The maximum allowed underground pressure is determined by the depth where the air is being contained. The reference point is the highest point in the cavern, or to be precise, it is the deepest point in the so called 'casing' (the steel pipe from the surface to the cavern).
A rule of thumb, also prescribed by SodM is 0,18 bar p/m. That means, for example, that with a casing depth of 1000 meters air can be stored at 180 bar maximum pressure. This depth, that determines the maximal permissible pressure, determines further the depth of the brine-air surface, or the maximum depth of the debrining string at which brine still can be pressed out of the cavern. This depth of the debrining string or the brine-air interface defines also the maximum volume available for storage.

A minimum pressure is stated to prevent significant creep of salt that leads to convergence of the cavern and intolerable soil subsidence and also to ensure stability of the cavern.

5.1.6 **Available working volume**

The necessary volume for the CAES project is dictated by power requirements and varies in this feasibility study between 0,6 and 1 Mm3

5.1.7 **Safety**

Air is being stored inside the cavern under high pressure. Air coming from the cavern is first transported through the down hole tubes and then through buried pipes. These high pressure pipes have to meet all safety standards.

From earlier studies for safety distances during high pressure blowout at 130 bar, has been concluded that for a vertical blow-out, there is no safety risk because of the vertical air direction. Also in a horizontal blow-out the safety-zone is very limited. However it has to be exactly quantified for air storage.

5.2 Technical issues

5.2.1 Solution Mining

KEMA has briefly studied the options of salt mining: solution mining and dry mining (drilling, similar to coal mining). Solution mining is commonly used in the Netherlands to obtain salt from several hundreds of meters depth without having to send staff down under. Salt is dissolved in water and pumped up, the salt-water mixture (brine) is transported in pipes to a salt manufacturing plant. Water then has to be taken out of the brine. Akzo, Nedmag and Frisia all use solution mining. Rock mining is used primarily in situations where salt is inside mountains and most excavating is horizontal rather than vertical. This situation can be found in countries outside the Netherlands. Dry mining enables the creation of underground space for other applications (research facilities, storage of nuclear waste), but requires considerable health and safety measures. According to AkzoNobel, the dry mined salt is of a different and lower quality than solution mined salt, which is another reason for AkzoNobel not to use this technology. At least theoretically, dry mining should involve less energy, since less water needs to be evaporated.
Salt industries present in The Netherlands are fully equipped for solution mining. In this study, KEMA has chosen to proceed with solution mining as the standard technology.

5.2.2 Tubing

There is a 13 3/8 inch casing (LCCS) in all existing caverns now. To build a gas-tight casing tube a 10 3/4 inch tube must be placed and cemented in the existing drill. In this cemented 10 3/4"casing pipe a 7 5/8 inch production tube can be placed for air in/out and a 5 1/2 inch tube for debrining at the initial stage where air volume has to be created

In a new drill (done by Akzo Nobel or any other company), a gas-tight cemented casing tube of 13 3/8 inch can be placed. In there a 10 3/4 inch production tube can be placed for air in/out and a 7 5/8 inch tube for debrining. Other drilling contractors can produce larger drilling and diameters of 18 ¾ " are quite well feasible. This also depends upon the required depth.

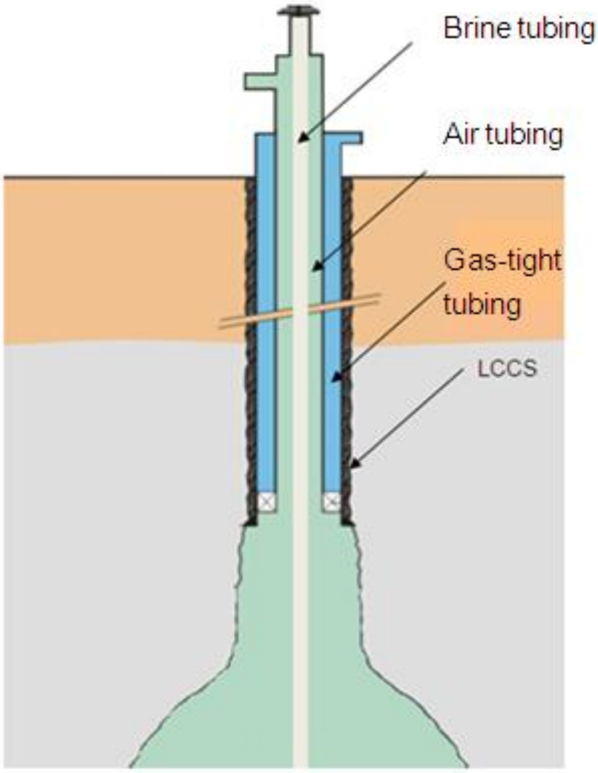


Figure 4 Cavern tubing

In table 3 are all diameters for the existing and new drilling.

Table 3 Summary diameters

Tubing	Existing drilling, inch	New drilling, inch
Casing	13 3/8	18 5/8
Gas-tight tubing	10 3/4	18 3/8
Air tubing	7 5/8	13 3/4
Brine tubing	5 1/2	7 5/8

5.3 Convergence and Subsidence

Cavern always have to stay under an external overpressure. Because of these stresses, the cavern creeps slowly and the volume of the cavern decrease. This is called convergence. The convergence velocity depends on the depth (h), the cavern temperature, the pressure (P1) and the rock and salt properties (P2).

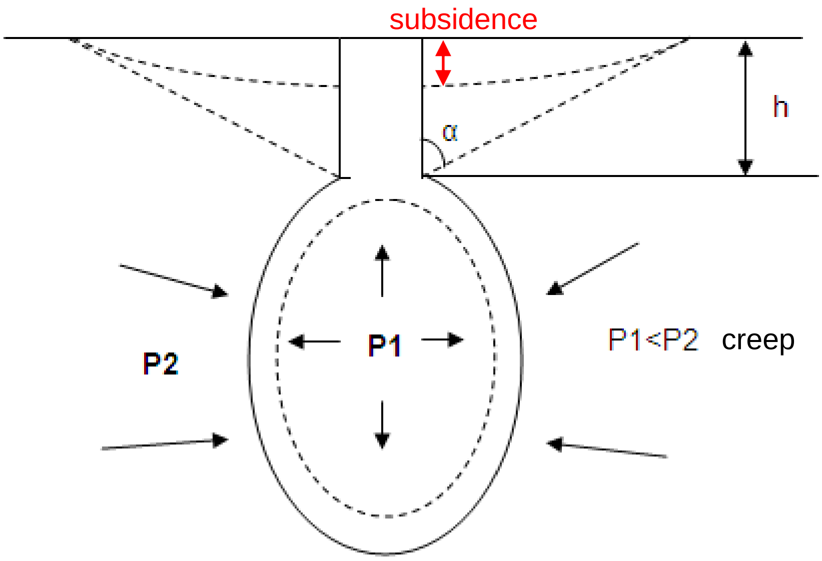


Figure 5 Soil subsidence

The total subsidence consists of the subsidence due to the gas- and salt extraction, natural processes and the effects of subsidence because of CAES.

From Gasunie study on subsidence, reported in the MER of gas buffer Zuidwending, at a pressure of 125 bar follows that the expected average subsidence in 2050 will be approximately 40 mm compared to 2007. The subsidence increases with decreasing average pressure and a growing number of caverns. This expectation are based on the calculations of The Bundesanstalt fur Geowissenschaften und Rohstoffen (BGR).

AkzoNobel estimates that operating within maximum and minimum permissible pressure will be no problem for the cavern stability and that the soil subsidence will be minor. Based on existing rules for the use of gas storage caverns AkzoNobel advises to keep the maximum permissible Delta P = 10 bar/day. This has been generally accepted by Staatstoezicht op de Mijnen (SodM). Gasunie indicates that much experience has been gained concerning cavern stability and integrity with this Delta P. If other Delta P is desired, a comprehensive study should be carried out.

5.4 Caverns for CAES in Groningen

The starting points are provided by KEMA Arnhem and the cases A11 and B11 were selected . Case A11 is based on a maximum pressure of 108 bar, case B11 on a lower pressure, around 75 bar. The maximum permissible Delta P in both cases is 10 bar per day.

Tabel 1

Case	**A11**	**B11**
Depth top cavern, m	600	415
Max Pressure top cavern, bar	108	75
Min pressure top cavern, bar	40	36
Min operating pressure top cavern, bar	98	65
Nr of vertical tubes to cavern	3	4
Volume storage, Mm3	0.596	0.629
Temperature storage, °C	30	30
Pipe length Well – Storage, m	600	415
Diameter, m	0.25	0.25

Because of operating at the maximum allowable pressure is most beneficial for the integrity and stability of the cavern, in first instance was chosen to go look at case A11, because of operating most closely to the maximum allowable pressure in the cavern. Operating at lower pressures is possible but leads to more subsidence then there should be a comprehensive study to come to stability and convergence of the cavern and the effect on soil subsidence.

5.4.1 **Location**

AkzoNobel has 5 caverns available for CAES, which are located in Heiligerlee (province of Groningen). This choice is based on case A11. Case B11 is, according to AkzoNobel, not realizable with the existing caverns because of their depths. For case B11 a new cavern should be developed or a check for stability and convergence/subsidence has to be done for the operation at lower pressure for the already mentioned 5 caverns. For a new cavern at lower operating pressure location Zuidwending is the best option because of shallow depth of the salt dome and the already existing infrastructure.

The aforementioned selection criteria have been used to evaluate the suitability of the 5 caverns. The five selected caverns are HL-A, HL-B, HL-F, HL-G, and HL-I. In Figure 3 is an overview containing the main characteristics of these 5 caverns.

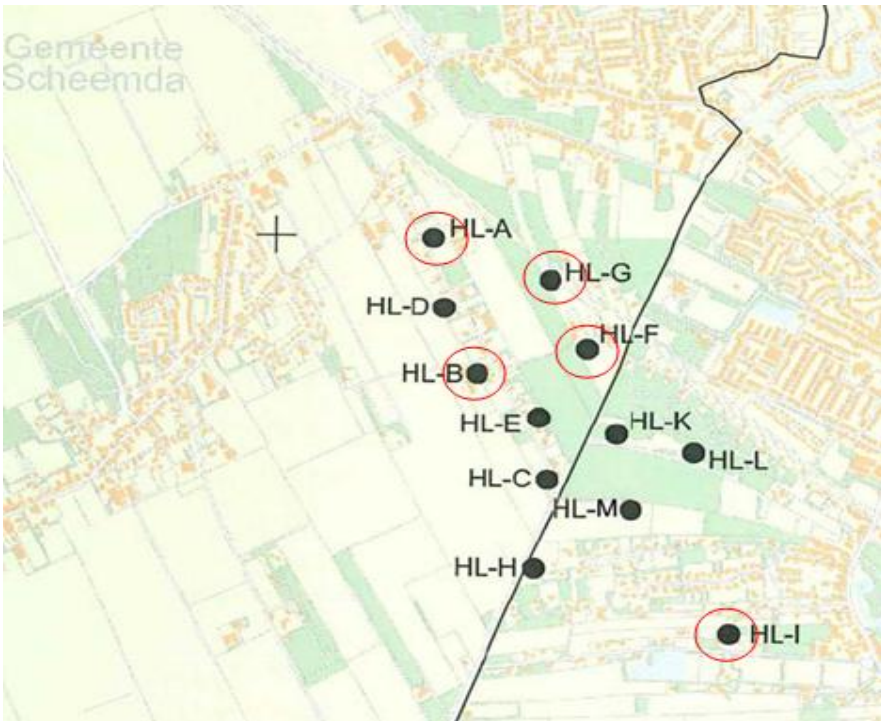


Figure 2 *Cavern selections for case A11*

In the table on the next page you can find data supplied by AkzoNobel concerning these 5 caverns. On this basis the caverns in Heiligerlee were assessed.

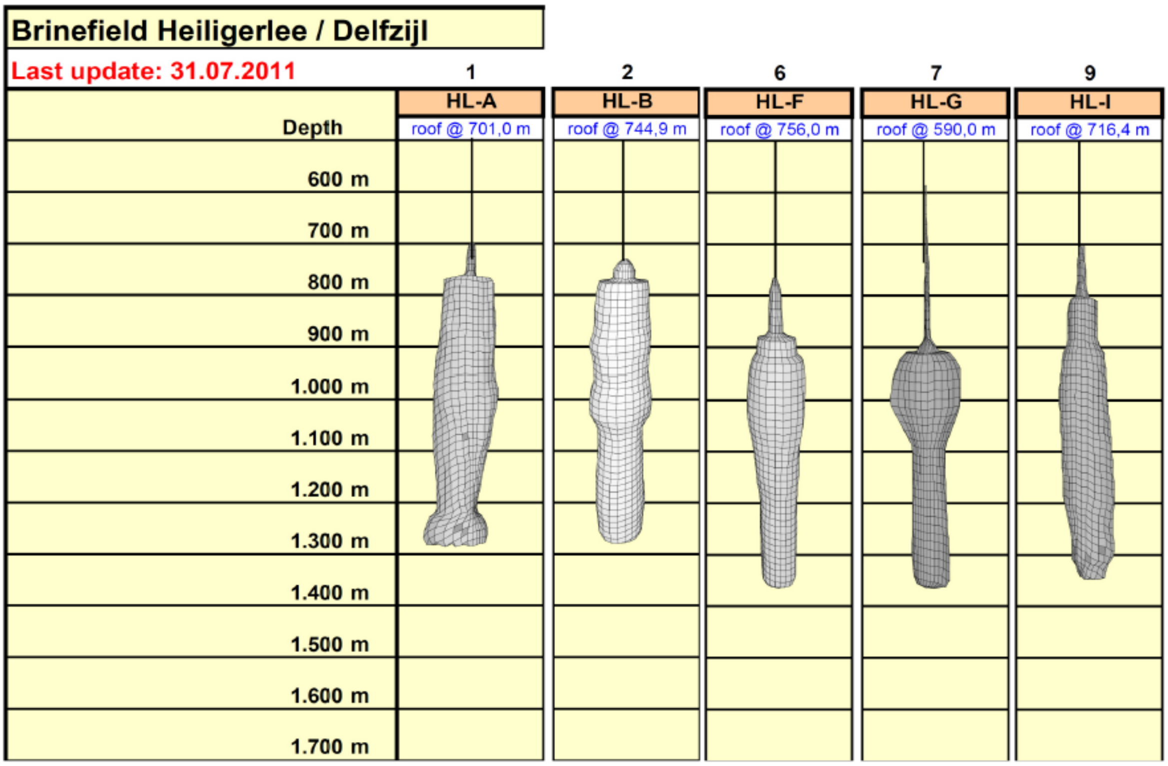


Figure 3 Caverns summary

Table 2 Caverns data

	HL-A	HL-B	HL-F	HL-G	HL-I
Distance to top	201	270	300	430	300
Depth cavern roof, m	701	744	756	590	716
Max pressure, bar	126	134	136	106	129
Air density, kg/m3	145	154	157	122	148
Average diameter, m	108	104	108	101	88
Distance to buildings, m	40	<5	42	72	14
Distance to next cavern, m	121	151	155	155	>150
Max available volume, Mm3	1.5	2.0	1.6	n.a.*	1.1
Diameter casing, inch	13 3/8	13 3/8	13 3/8	13 3/8	13 3/8
Diameter gas tube, inch	7 5/8	7 5/8	7 5/8	7 5/8	7 5/8
Gas tube length, m	701	744	756	590	716
Diameter brine tube, inch	5 1/2	5 1/2	5 1/2	5 1/2	5 1/2

* not assessed

5.4.2 Cavern choice Groningen

Table 2 shows that cavern A is unsuitable for air storage because the distance to the nearest caverns is less than 150 meters, that makes the stability and integrity of this cavern insufficient.

Caverne G falls out of the selection because of the volume. This cavern has now a thin neck. In case when the neck is extended, then HL-G would be similar to HL-A in terms of usage properties.

Caverns B and I are situated very close to buildings making them less suitable for safety reasons. In a previous study "keuzeproces stikstofbuffer Heiligerlee" the safety distance by blow-out of high pressure pipe has been determined. It was concluded that a vertical blow-out forms no risk because the gas flow is directed upwards. By a horizontal blow-out a safety distance of some tens of meters should be kept.

Caverne F meets all rock-mechanical and safety criteria and has sufficient volume. This caverne meets all requirements now for use for CAES.

5.4.3 Cost indication Groningen

The existing drilling diameter is too small to meet the requirements of the current CAES project. For that reason multiple drillings per cavern should be performed. New drilling in existing caverns can be done without licensing. Indicative costs estimated for one new drilling with completion in an existing cavern are 2-3 Million EUR if carried out by third parties, and less (1-2 Million) if performed by AkzoNobel. AkzoNobel indicates that they can drill up to 13 5/8 inch casing max.

Extra borehole with completion: 4-5 MEUR per bore hole
The tubing-work: 1 MEUR per km customize
Existing drilling for CAES by AkzoNobel: 1-2 MEUR

5.5 Caverns for CAES in Drenthe

5.5.1 Location

In the subsurface policy plan of the province Drenthe the salt-dome Hooghalen, located between Assen and Beilen, is foreseen as possible suitable location for energy storage in the form of compressed air. The salt-dome Hooghalen seems to be suitable for this because of the combination of the shallow location and the thickness of the dome. There are no specific restrictions to a CAES plant as far known within this area

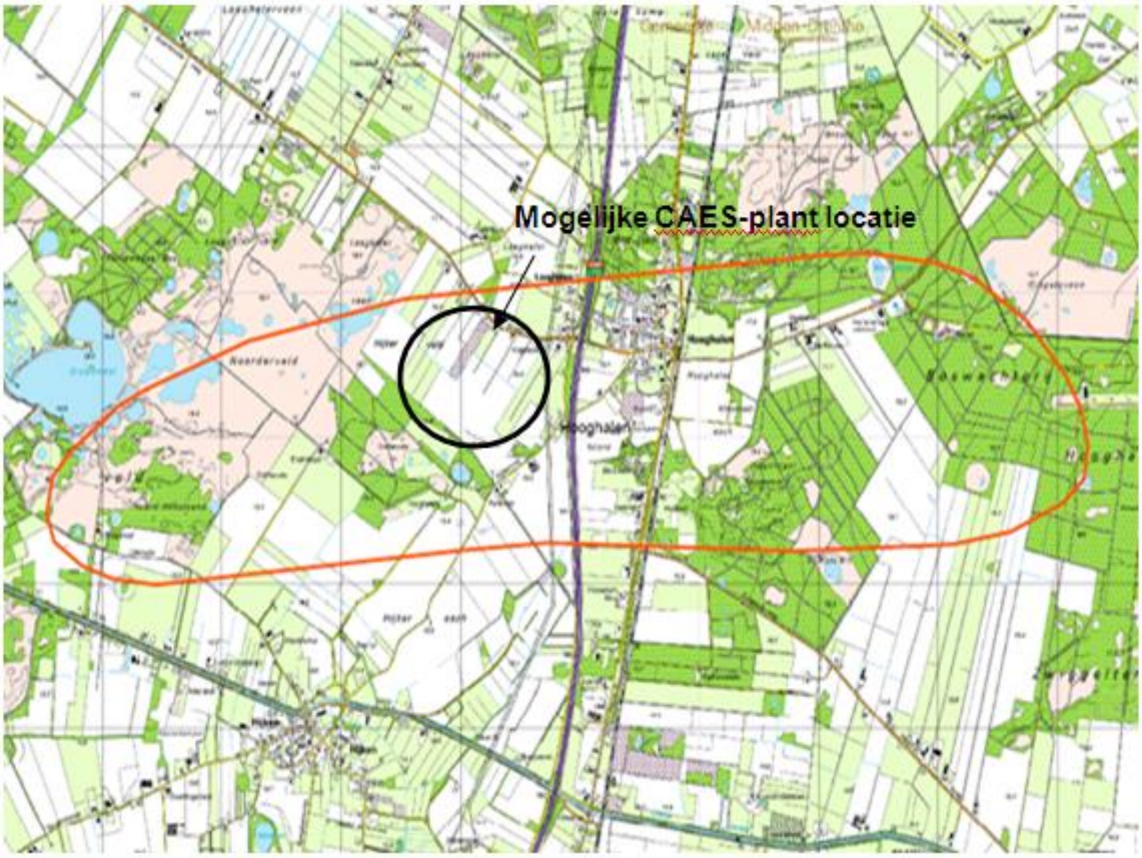


Figure 2 Location Hooghalen

5.5.2 **Cavern design for Hooghalen**

TNO has created, on the basis of available seismic and drilling data, a geological model in which the thickness and depth of the various geological formations is indicated. According to this model is the highest point of the salt pillar in Hooghalen just 300 meters below NAP. Conservative assumes a depth location of salt on the top of the 400 meters. The 3D-visualization is displayed in Figure 3.

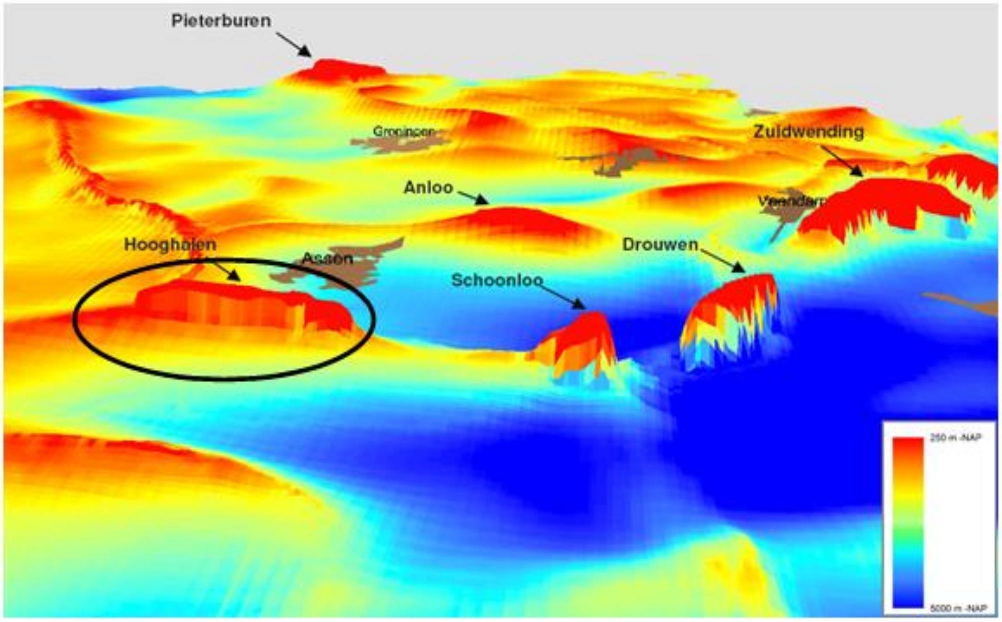


Figure 3 3D-visualisation of the top of Zechstein

According to these data and cavern directives of the German bureau IFG a number of caverne parameters (such as caver-roof, depth and the maximum allowable pressure) can be determined. The creation is created by dissolving salt, which is located in the subsurface, with water. The dissolved salt (brine) is pumped to surface.

After a deep hole is drilled, in which two twined tubes are placed, the water is pumped in the underground salt-layer by one tube and saturated brine goes is via the other tube to the surface. Before the brine can be processed, it must be saturated in existing salt winning cavern. The brine has to be degassed and filtered. Saturated brine has to be transported through a pipeline to the production location and processed.
Creating a cavern lasts from two to three years before the desired shape and size of approximately 0,5-0,6 Mm3 content is reached.

The following cavern parameters can be determined for potential new caverns in Hooghalen for CAES usage. Because of uncertainty in depoth of the cavern, a range in depth of the cavern roof and max. pressure of the cavern are indicated. For reason of comparison with the Heiligerlee case, the depth of 400 meter and pressure of 75 bar will be used

Table 2 permanent cavern parameters

	HH
Distance to top, m	200 - 400
Depth cavern roof (H1), m	400-600
Max pressure, bar	75 to108
Distance to buildings (assumption), m	>40
Distance to next cavern, m	>150
Maximal depth of brine level	640-840

The shape of the cavern depends on the salt layers properties, the stability criteria and the necessary volume. For the caverns in the depth range of 500-1000 meter is recommended to make sphere-or pear-shaped caverns. These forms are chosen to ensure the stability of caverns. Cavern diameter, length and maximum pressure determine together the maximum volume available for the air storage. In table 3 the parameters of a possible cavern are displayed.

Table 3 Variable cavern parameters

Average diameter (d), m	56-60
Cavern length (H2), m	240
Available air volume, Mm3	0,5-0,6

Once a cavern has the correct shape and volume, it can be filled with air. The air, injected under pressure in the cavern, presses the brine out of the cavern. This step is called debrining. When all brine is pushed away by air, the cavern can be used for the CAES.

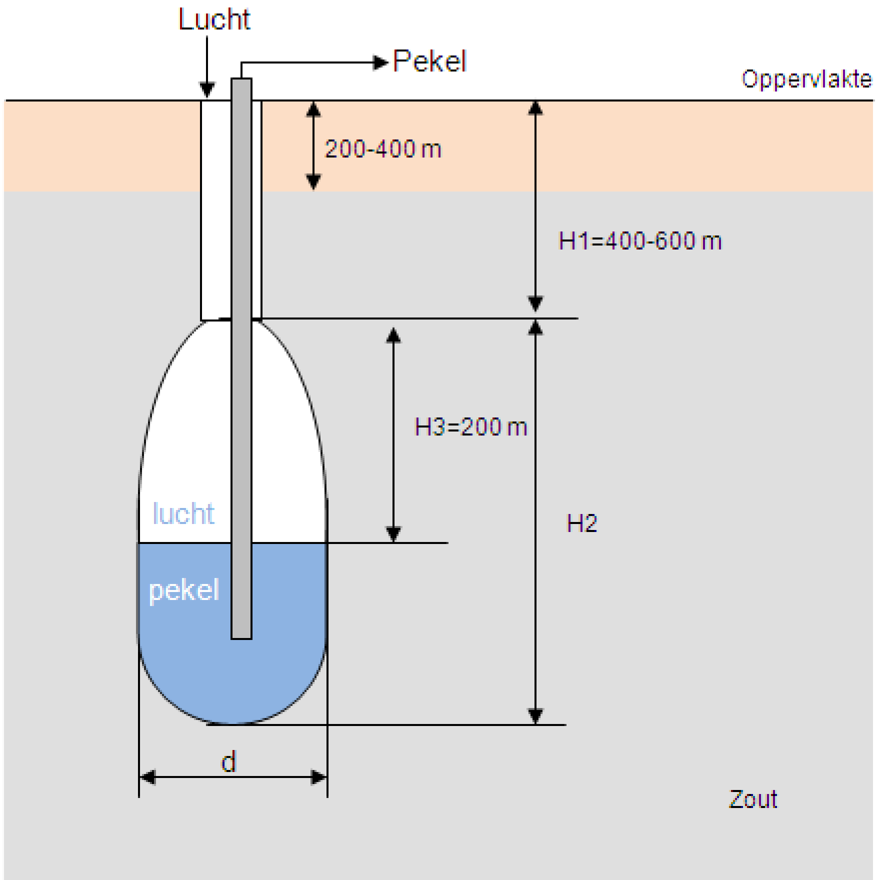


Figure 3 Cavern parameters for new cavern (in Hooghalen salt dome)

5.5.3 **Costs indication Drenthe**

The entire process of developing a new drilling site (study of execution) takes around10 years. The related costs (brine installation, pump station, degasser and pipelines) depend, amongst others, on the length of the pipelines system, necessary for brine transport. Indicative cost for a complete new location, including salt production facility is 50 MEUR.

Indicative cost estimate for a new bore with completion: 4-5 millions EUR if carried out by third parties, less if performed by AkzoNobel. AkzoNobel indicates that they are up to 13 5/8 inch casing.

Extra boring with completion: 4-5 MEUR per bore
The pipe work: 1 MEUR per km
Brine pipeline to brine processing-50 MEUR
Development of a new drilling site-50 MEUR.

Developing a new cavern takes 3 years for a desired volume of 0.6 Mm3 with a brine rate of 250 m3/hour (which is the maximum rate).

6 PRELIMINARY DESIGN OF THE SELECTED CAES CONCEPT

6.1 Description of the recuperated optimized CAES

A model of an optimized recuperated CAES plant has been realized using the proprietary software SPENCE. The model is based on a layout as the one schematized in Figure 6-1 that includes: intercooled compressor, piping (under and above ground), cavern, burners and tail-end heat exchanger (regenerator).

The objective of the model is to develop a preliminary design of the plant, and thus to gain insight into performance of the plant and equipment sizing.

The plant is design to deliver 300 MW of electricity to the grid at nominal conditions.

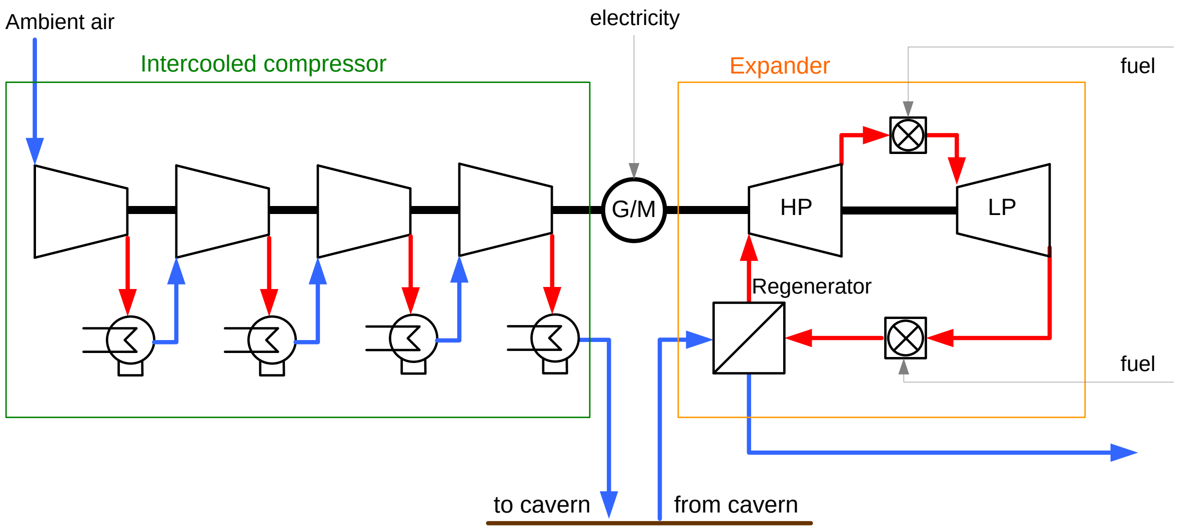


Figure 6-1 Scheme of the optimized CAES layout

During "storage mode" operation in off-peak hours the electricity from the grid is used to compress the air into the underground reservoir. The compressor withdraws air from the atmosphere and compresses it to the storage pressure which varies between the maximum and the minimum operating pressure, namely the min and max allowable pressure of the reservoir. To reduce compressor power demand a four stages intercooled compressor is used. The heat extracted from the hot air in the intercoolers is dissipated into the environment by a cooling system.

During "generation mode" operation in peak hours the electricity is produced by an expander uses the pressurized air stored into the underground reservoir. The air is withdrawn from the reservoir at a temperature around 30 °C and is heated up to 600 °C in the regenerator by hot exhaust gases exiting the second burner. The turbine is split in two stages, high pressure (HP) and low pressure (LP), in order to re-heat the gas before the low pressure stage and thus increase gas turbine efficiency.

The exhaust gas from the LP stage is re-heated by the second burner to provide enough heat for the recuperative heat exchanger downstream. This configuration of the expander is described in [Tuschy 2004] and has the advantage of a higher efficiency with respect to the typical recuperated configuration of the expander (as used in the McIntosh plant). During "generation mode" the expander uses natural gas, therefore connections to the natural gas network is needed.

The motor used to drive the compressor during "storage mode" is used as generator for the gas turbine during "generation mode". The compressor, the generator and the expanders rotate around the same shaft. A system of clutches on the shafts allows to disconnect the gas turbine when the compressor is operating and to disconnect the compressor when the gas turbine is operating.

6.2 SPENCE model

The model has been realized in SPENCE (see APPENDIX II for a description of the software) following the same plant concept presented above. The model can run in both operational modes, namely the "generation" and "storage" modes. The model simulates the CAES plant operation with the "recuperated optimized" configuration. The most important results that are obtained from the simulation are:

- Round-trip efficiency of the plant
- Compressor power at nominal capacity
- Fuel consumption at nominal capacity
- Air flows during charge and discharge
- Cooling duty for the intercoolers.

Round-trip efficiency indicates the ratio between the electricity that is sent to the network over the sum of the electricity used in compressor during injection and the energy added with the fuel. The efficiency is calculated accounting the hours of injection and production during an entire cycle, thereof is defined as "round-trip".

Round trip efficiency is calculated as follow:

$\eta_{roundtrip} = MWe_{generator} \times h_{production} / (MWe_{compressor} \times h_{injection} + MWth_{fuel} \times h_{production})$

Figure 6-2 and Figure 6-3 show examples of the flowsheet of the CAES model, representing the compressor and the expander sections, respectively.

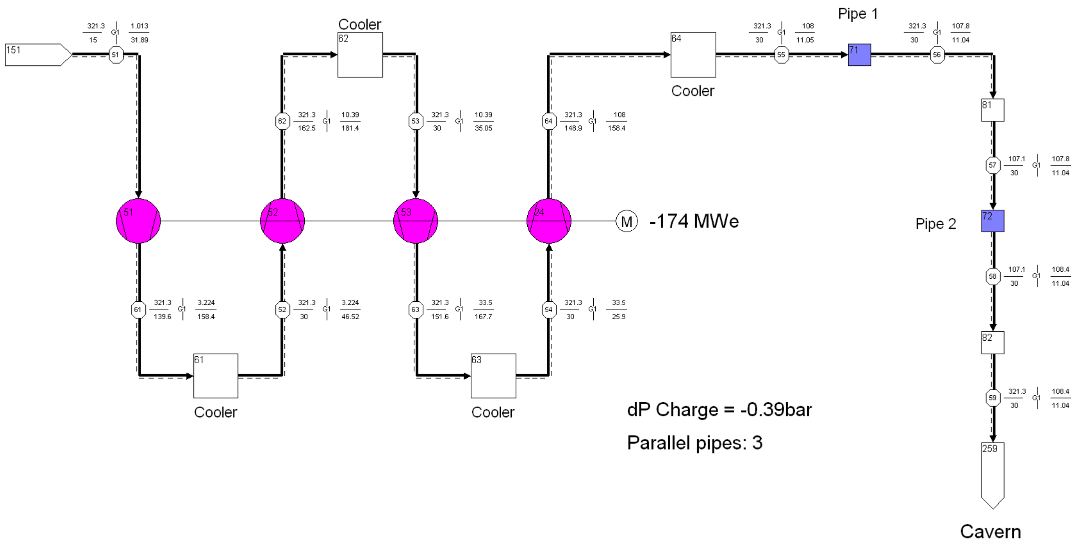


Figure 6-2 Example of flowsheet of the compressor as modeled in SPENCE

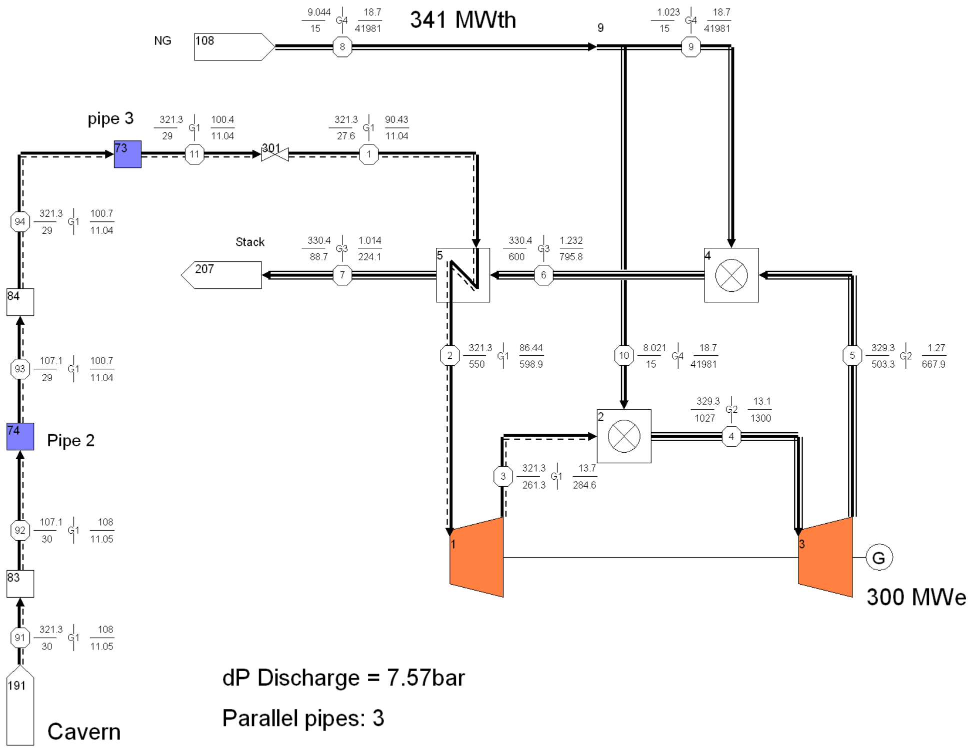


Figure 6-3 Example of flowsheet of the expander as modeled in SPENCE

6.3 Plant design assumptions

The following table summarizes the main assumptions used for the design of the CAES plant.

Table 6-1 Main assumptions of the CAES plant

Parameter	Unit	Value
Plant size (net production)	MWe	300
Ambient condition		ISO (15°C, 1.013 bar)
Cooling water temperature	°C	15
Natural gas HHV (Slochteren gas)	MJ/kg	44
Temperature approach regenerator	K	50
Mechanical efficiency compressors	-	0.98
Isentropic efficiency compressors	-	0.90
Mechanical efficiency expanders	-	0.98
Isentropic efficiency expanders	-	0.88
Ratio flow Expander/Compressor	-	1

In this study the CAES plant is designed with a ratio between the compressor nominal air flow and gas turbine nominal air flow that is equal to 1. In other words this means that if the compressor is operated for 6 hours at nominal capacity, then the amount of air stored in the cavern is enough to operate the gas turbine at nominal capacity for 6 hours.
If the ratio is 0.5 then this means that for 6 hours of compressor operation at nominal capacity the gas turbine can be operated only for 3 hours at nominal capacity.

The flow ratio between expander and compressor is important to determine the design capacity of the compressor and the gas turbine. The selection of the optimal Expander/Compressor ratio depends on the way the plant will be operated and on the minimization of costs. In this study the design ratio is assumed equal to 1.

6.4 Cavern characteristics

The cavern characteristics play a major role in defining the operating condition of the plant due to the close interaction between the cavern and the plant.
The most important parameters to be considered in the model are the following:

- Maximum and minimum operating pressure
- Cavern volume
- String length and diameter from cavern to well head
- String length and diameter from well head to CAES plant.

Maximum and minimum operating pressure

Each cavern has a maximum pressure limit that depends on the depth of the cavern itself. The deeper is the cavern the higher is the maximum pressure. For the integrity of the cavern and the concrete casing of the strings it is not possible to exceed this limit during operation.
It is assumed in this case that a daily pressure variation of 10 bar inside the cavern is the maximum allowable for structural integrity of the cavern; thus, the lower pressure limit is always assumed as 10 bar lower than the maximum limit.

Cavern volume
The volume of the cavern and the limits on operating pressure define the amount of air that can be stored. During charging mode the air can be injected in the cavern till the maximum pressure is reached. For the same reason, during discharging mode the air can be extracted from the cavern till the lower pressure limit is reached.
If the available volume is given, the max volume of air that can be used during CAES operation corresponds to the difference between the stored air volume at maximum and minimum operating pressures.
In cavern previously used for salt extraction is not possible to remove all the brine (pekel) that is present in the cavern, therefore the available volume for air storage is less than the total volume of the cavern.

Length and diameter of the string from cavern to well head (underground)
In existing caverns the piping connecting the surface with the cavern is already in place. However, in most cases the existing string is too small for the volume flow of air needed in CAES and a new, bigger, string must be used. Using both the existing string and the new one is also an option when air flows are large.
Enlarging the existing string is not a solution since it more difficult than drilling a new one, although the realization of a new string can be hindered by permitting or safety issues.
The larger is the diameter of the string the lower will be the pressure loss of the air flow, however, the maximum (internal) diameter possible is 340 mm for a new string.
The length of the string is approximately equal to the depth of the cavern roof. In this study they are assumed to be equal.

Pipe length and diameter from well head to CAES plant (aboveground)
The aboveground pipe connecting the well-head to the CAES plant is also an important aspect to be considered. The plant could be located some kilometers away from the well and therefore the air pipe must be properly design to minimize pressure drops and costs. In this study it is assumed that the aboveground air pipe has an (internal) diameter of 750 mm.
Results demonstrate that pressure drops are acceptable with this diameter.

6.5 Cavern characteristics for the Groningen region

In the Groningen region several salt caverns already exist in different location and with different size and depth. They have been created in the past by the industrial activity of salt extraction from underground salt domes. AkzoNobel is proprietary of many of those caverns and has information on the characteristics of the salt cavern.

The most suitable caverns have been selected by KEMA in consultation with AkzoNobel. For the Groningen region AkzoNobel and KEMA individuated 5 possible caverns to be used for CAES in Heiligerlee, although just one out of the 5 caverns can be used for CAES purposes. The suitable cavern is the cavern 'HL-F' located in Heiligerlee. Table 6-2 summarizes the data of cavern HL-F used in simulation of the CAES plant with SPENCE.

Table 6-2 HL-F cavern characteristics

CAVERN HL-F		
Location		Heiligerlee (Groningen, NL)
Volume (available for air storage)	m^3	1.600.000
Depth (of cavern roof)	m	756
Max pressure	bar	136
Max daily pressure excursion allowable	bar	10
Temperature	°C	30
String diameter (existing)	mm	193
Max diameter for new string	mm	340
Aboveground pipe diameter	mm	750
Distance from well-head to CAES plant	km	10

6.6 Cavern characteristics for the Drenthe region

Salts domes at accessible depths are however present also in this region and the creation of salt cavern is possible. For the Drenthe case a new cavern has to be leached and the preliminary design on the plant has been made by assuming more ideal cavern characteristics. This also gives the opportunity to get insight in the effect of cavern depth/pressure.
Table 6-3 summarizes the assumption for the cavern characteristics used in simulation of the CAES plant for the region of Drenthe.

Table 6-3 Assumed cavern characteristics for Drenthe region

Location		Drenthe region
Depth (of cavern roof)	m	400
Max pressure	bar	75

Max daily pressure excursion	bar	10
Min pressure	bar	65
Temperature	°C	30
Air string diameter	mm	340
Number of air strings from surface to well		2
Aboveground pipe diameter	mm	750
Distance from well-head to CAES plant	m	500

In this case the aim is to create and use a cavern less deep as possible to minimize the operating pressure and thus the equipment costs. In fact higher operating pressure is not needed and has no benefit on the round-trip efficiency. Moreover operating at higher pressures increases the cost of the equipment.

For this reason an optimistic depth of 400 m has been used although it is not certain that a cavern at this depth is possible to realize. The pressure maximum operating pressure is estimated to be circa 75 bar.

It is assumed that the plant can be located close to the well-head therefore a distance of 500 m from well-head to plant is assumed, instead of 10 km as expected for the plant location in Heiligerlee (Groningen).

6.7 Cases modeled

SPENCE simulations have been performed for six different cases, four cases for the plant in Groningen (using cavern HL-F in Heiligerlee) and two cases for the plant in Drenthe:

Case 1: the plant uses the cavern HL-F, and is designed for 6 hours in charging mode and 6 hours in discharging mode. A new single string is used in place of the existing one (1 string).

Case 2: the plant uses the cavern HL-F, and is designed for 6 hours in charging mode and 6 hours in discharging mode. The new string is used together with the existing one (2 strings).

Case 3: same characteristic of Case 1 but designed for 12 hours in charging mode and 12 hours in discharging mode.

Case 4: same characteristic of Case 2 but designed for 12 hours in charging mode and 12 hours in discharging mode.

Case 5: the plant uses a cavern with characteristics given in Paragraph 6.6, and is operated 6 hours in charging mode and 6 hour in discharging mode.

Case 6: the plant uses a cavern with characteristics given in Paragraph 6.6, and is operated 12 hours in charging mode and 12 hour in discharging mode.

The cases 3 and 4 have been included to verify that the volume available is enough to operate the plant for 12 hours at full capacity, although the design operation time is 6 h.

Cases with double string, namely cases 2 and 4 have been additionally simulated to observe the effect of using the existing string in combination with a new one. It has been found that the existing string is not sufficiently large for the air flow required therefore a new string is necessary, to be used alone or in combination with the existing. If the existing string is used together with the new one then the flow section for the air could be increased further and consequently pressure drops are reduced with improvement of the round-trip efficiency.

Case 5 and 6 represent a plant for the Drenthe region; for these two cases the cavern characteristics are assumed (see Paragraph 6.6).

6.8 Results for CAES plant using a salt cavern HL-F in Heiligerlee

Table 6-4 shows main results of the simulations for the CAES plant in Heiligerlee (Groningen). The flow sheets of the SPENCE models for the 5 cases are included in APPENDIX III.

Table 6-4 Results of SPENCE simulations for the CAES plant in Groningen

Case nr.		1	2	3	4
		cavern HL-F 6/6 1 pipe	cavern HL-F 6/6 2 pipes	cavern HL-F 12/12 1 pipe	cavern HL-F 12/12 2 pipes
General					
Min pressure	bar	132.3	132.3	128.7	128.7
Max pressure	bar	136.0	136.0	136.0	136.0
Volume cavern	m3	1600000	1600000	1600000	1600000
Round trip efficiency	%	57.9	58.0	57.9	57.9
CO_2 emissions	kg/MWh	230.9	230.9	231	231
Stack temperature	°C	86.0	86.0	86.2	86.2
Ratio mass flow Exp/Comp		1	1	1	1
Expander					
Discharging time	h	6	6	12	12
Power expander	MWe	300.0	300.0	300.0	300.0
Sendout mass flow	kg/s	306.9	306.5	307.7	308.1
Energy produced	MWh	1800.0	1800.0	3600.0	3600.0
Fuel input	MWth	340.3	340.3	340.4	340.4
Fuel input	kg/s	9.0	9.0	9.0	9.0
Fuel input	Nm3/s	10.8	10.8	10.8	10.8
Compressor					
Charging time	h	6	6	12	12
Power compressor	MWe	178.0	177.0	177.0	178.0
Injection mass flow	kg/s	306.9	306.5	307.7	308.1
Energy stored	MWh	1067.0	1063.0	2128.0	2136.0
Duty coolers	MWth	180.4	179.7	179.8	180.5
Pipe system					
Underground pipe length	m	10000	10000	10000	10000
Underground pipe length	m	756	756	756	756
Pressure drop discharging	bar	6.83	5.50	5.62	6.97
Pressure drop charging	bar	6.52	5.30	5.41	6.65

The CAES plant has a round-trip efficiency around 58% for all four cases. The efficiency of this plant is higher than the efficiency of the simple recuperated plant (MacIntosh) which is around 54% [Bieber 2010].

The compressor power required at full capacity is about 177-178 MW_e, corresponding to the power that can be absorbed from the grid during charging mode operation. The four intercoolers of the compressor dissipate 179-180 MW_{th} of heat through the cooling system. The gas turbine needs natural gas supply of 10.8 Nm^3/s during expander operation at full capacity.

In the existing cavern HL-F the maximum pressure allowed is 136 bar. Given the available volume of 1.600.000 m^3 the model calculates the corresponding minimum pressure in the cavern during operation. For cases 3 (and 4) the amount of air to be stored is double than for cases 1 (and 2). The resulting minimum pressures are therefore 128.7 and 132.3 bar, respectively. A different operation time has effect only on the amount of air stored and the pressures inside the cavern while variations on the other parameters are negligible.

Cavern HL-F has enough volume available to operate a 300 MW_e plant for 6 hours. The corresponding pressure variation in the cavern during operation is about 4 bar (from 136 to 132.3 bar). If the plant is designed for 12 hours operation the volume of the cavern is still sufficient, in fact also in this case pressure variation is about 8 bar (from 136 to 128.7 bar), thus still within the max variation of 10 bar. This result can also be interpreted in a different way: the plant designed for 6 hours of cyclic operation in special situations can generate electricity for 6 extra hours without exceeding the maximum pressure variation in the cavern. This is relevant because creates additional flexibility for the plant operation. Even if the plant is designed to operate continuously for a certain numbers of hours, discontinuous operation is still possible as long as volume and pressure in the cavern are kept within operating limits. Moreover, partial load operation is also possible: for instance a plant design to operate at 6h for full capacity can operate for about 12 hours at 50% capacity. However, this may reduce the round-trip efficiency somewhat.

Results also show that using a single new string or the combination of the new with the existing doesn't have significant influence on the fuel consumption and the round trip-efficiency (+0.1%-points using the old string in combination with the new one). This means that a new string with an internal diameter of 340 mm is sufficient for a 300 MW_e plant; the additional use of the existing string to increase the air flowing section, and thus reduce pressure drop, has positive but limited effect on the efficiency.

6.9 Results for CAES plant using a salt cavern in Drenthe

It is important to highlight that for the cases of Drenthe the volume of the cavern is not given but results from the simulation. This is because the cavern in Drenthe doesn't exist yet and can be created based on the requirements for the CAES plant. The volume is calculated from the amount of air to be stored for 6 and 12 hours, assuming a maximum pressure variation of 10 bar between the "empty" and the "full" cavern.

Table 6-5 Results of SPENCE simulations for the CAES plant in Drenthe

Case nr.		5	6

		Drenthe 6/6	Drenthe 12/12
General			
Min pressure	bar	65	65
Max pressure	bar	75	75
Volume cavern	m3	620000	1240000
Round trip efficiency	%	59	59
CO_2 emissions	kg/MWh	233	233
Stack temperature	°C	94	94
Ratio mass flow Exp/Comp		1	1
Expander			
Discharging time	h	6	12
Power expander	MW_e	300	300
Sendout mass flow	kg/s	340.9	340.9
Energy produced	MWh	1800	3600
Fuel input	MW_{th}	343	343
Fuel input	kg/s	9.1	9.1
Fuel input	Nm3/s	10.9	10.9
Compressor			
Charging time	h	6	12
Power compressor	MW_e	166	166
Injection mass flow	kg/s	341	341
Energy stored	MWh	999	1997
Duty coolers	MW_{th}	166	166
Pipe system			
Underground pipe length	m	750	750
Underground pipe length	m	340	340
Pressure drop discharging	bar	1.97	1.97
Pressure drop charging	bar	1.94	1.94

Simulations of the CAES plant for the Drenthe cases indicate a round trip efficiency around 58.9%, thus about 1%-point higher than the Groningen cases. The improvement in the efficiency is given by the fact that the plant is operated at a lower pressure and consequently the power demand of the compressor is lower. Additionally, pressure losses are reduced because the distance from the well to the plant is only 500 m and not 10000 m as assumed for Groningen.

The gas turbine needs natural gas supply for an amount of 10.9 Nm^3/s at during expander operation at full capacity. The Drenthe CAES plant designed for 6 hours of full load operation requires a cavern of approximately 620.000 m^3. If it is designed for 12 hours of full load operation then the cavern volume needed is 1.240.000 m^3. The compressor power required at full load is about 166 MW_e that is circa 10 MW_e lower than the Groningen plant. The intercooler duty is also reduced to 166 MW_{th}. The compressor has a lower consumption in this case because the pressure of the cavern is lower than the pressure in cavern HL-F (cases 1, 2, 3,4) and less pressure losses occurs in the piping that connect the cavern to the plant equipments.

If it is possible to realize a cavern with similar characteristics to those assumed in this study in the Drenthe region, then it would be possible to operate a CAES plant of 300 MWe with a slightly improved performance compared to the same plant installed in Heiligerlee using cavern HL-F.

6.10 **Grid connection**

KEMA has discussed grid connection of the CAES plant with TenneT (Peter Eilers and Kees Jansen). After comments received in the partner meeting, a further telephone conversation has been held with Kees Jansen.
Connecting 300 MW to 110 kV is no longer policy of TenneT. It has been done in the past, but is no longer a choice offered. Technically, it is still feasible.
TenneT has indicated that the 110 kV network in the Groningen area is at maximum use already. An additional power plant in that network would certainly lead to congestion. Detailed studies of the available capacity would be required to see how and where a CAES plant would fit in and how much congestion would take place.

At first glance, the transformer station at Meeden (several km from Zuidbroek) offers 110, 220 and 380 kV voltage connection. The overhead power line between Eemshaven and Meeden is most likely going to be upgraded to a 380 kV connection. Therefore, the Meeden station will be upgraded to 380 kV. The current 380 kV station is at its maximum capacity at the moment.
Currently a series of developments is ongoing in the Northern part of the Netherlands: 600 MW of offshore wind will be connected; a power cable to Denmark and perhaps a second cable to Norway will arrive in Eemshaven. New large size onshore wind farms will be realized in the region. A new 380 kV power line will be realized between Groningen and the Randstad. Further increase of power demand may result in changes and upgrades of the lower voltage networks in the area. For a development that will have a long lead time, like CAES, it is not efficient to spend a long time on identification of the best connection point, if this will probably change in several years.

The TenneT preference (and proposal) at this moment is to connect a CAES plant situated in Zuidbroek at 220 kV level either at Weiwerd (Delfzijl, 18 km straight line), Zeyerveen (Assen, 31 km) or Vierverlaten (west of Groningen, 27 km). Given the distance, this results in considerable costs for grid connection. In a more concrete stage of project development, in depth discussions will have to be held with TenneT about the alternative possibilities for grid connection. TenneT is open for that, but at this time, they expect many changes in the infrastructure in the North of the Netherlands so TenneT cannot offer a suitable alternative.

A power plant situated near Hooghalen will preferably be connected in Zeyerveen (11 km straight line).

7 ECONOMIC ANALYSIS - INVESTMENTS

7.1 Investment cost of a CAES plant

A first approach to determination of CAES plant cost has been the review of cost indication available trough literature. Table 7-1 summarizes the most relevant cost indications found in literature.

Table 7-1 - CAES Plant investment costs including cavern development/completion

Source	[RidgeEnergy 2005]	[Knoke 2002]	[Knoke 2002]	[EPRI 2004]	[Radgen 2010]
Reference case	Ridge Energy study	MacIntosh investment	Norton feasibility	General estimate	General estimate
Specific plant cost (per kWe)	605	570	444	580	560
Year	2005	2002	2002	2004	2010
Currency	$	$	$	$	EUR
Actualized cost 1) 2) (EUR/kWe)	**707**	**832**	**648**	**762**	**560**
Total cost 3) (MEUR)	**212**	**250**	**194**	**229**	**168**

1) Costs are actualized using the IHS CERA Power Capital Costs Index (PCCI) North America, may 2011 (http://www.ihsindexes.com)
2) Currency conversion: 1 $ = 0.75 EUR
3) For a 300 MWe plant

The investment costs found in literature ranges from 560 to 830 EUR/kW, corresponding to a capital cost of 168-250 MEUR for a CAES plant of 300 MW of maximum electrical output capacity. The literature costs include costs for the plant and the cavern development and completion. The exact cost components that are included in these costs from literature are not always explained. Therefore this range is indicative for a generic CAES installation.

CAES investment cost are often compared with gas turbine (GT) plant investment costs. However, it is not correct to compare specific investment costs, as the output power for a similar sized CAES turbine and GT are different. For a GT, 60% of the turbine work is required to drive the directly coupled compressor. A 120 MWe GT turbine produces over 300 MW work of which 180 MW is used internally. A CAES plant has a separate, electrically driven compressor and the total expander work can be used to drive the generator.
The output power of a CAES plant has to be multiplied with a factor 0.4 to get a similar sized GT when comparing prices. So a CAES turbine that has a nominal output of 300 MWe should be compared to a gas turbine size with a nominal output of around 120 MWe.

The total investment cost for a 120 MWe GT is 78-84 MEUR[1] (650-700 EUR/kWe), which is in fact much lower than the 300 MWe CAES total investment cost range of 168-250 MEUR (560-830 EUR/kWe), while the specific costs are similar. This example show that comparing specific costs should be avoided or the specific costs of a CAES turbine have to be increased by a factor of 2.5 to compensate for the different process design.

The cost of a CAES plant is higher than a GT plant for the following reasons:

- The CAES compressor has a higher pressure ratio since it has to compress the air up to 140 bar, instead of 20-30 bar as in typical GT cycles,
- The CAES compressor also includes an intercooling and after-cooling system
- A cooling system must be included at the CAES plant to serve the intercoolers and after coolers of the compressor,
- CAES plant includes the cavern development and the system of high pressure piping and valves that connect the cavern to the plant equipment,
- The CAES expander systems includes a regenerator which is a gas/gas heat exchanger of significant size (that operates at high pressure on one side)
- The CAES expander train operates at higher pressure compared to normal GT pressures.

KEMA estimated the investment costs for a CAES plant based on the information and knowledge available. This cost estimation is tailored for a plant layout as considered in this study (see Chapter 6) and considers for table 7-2 that the cavern already exists and for table 7-3 that a total new site for cavern creation has to be developed.
The estimation has a significant uncertainty due to the fact that the layout of the CAES plant is not an off-the-shelve commercial layout. Moreover, the preliminary design may be optimized further before the realization through a techno-economic optimization process that is not yet applied in this study. Table 7-2 summarizes the cost estimation made by KEMA for an existing cavern.
For the power plant the cost of the main equipment has been budgeted and a factor of 3 has been used for estimating the total cost of installation and construction on the facility. For For cavern and connection total cost have been directly indicated.

[1] GT specific investment cost of 650-700 EUR/kWe [ETSAP 2010]

Table 7-2 CAES plant investment cost estimate (existing cavern)

part	component	amount	unit	specific cost	unit	base estimate (M€)	low estimate -40% (M€)	high estimate +40% (M€)
power plant	compressor	1		43000000	€	43	25.8	60
(component cost)	expander	1		15000000	€	15	9	21
	generator/ motor	1		6000000	€	6	3.6	8.4
	regenerator	1		6000000	€	6	3.6	8.4
	cooling system	1		3000000	€	3	1.8	4.2
	total installed cost					219	131	307
cavern	completion exisiting cavern (new string)	1		6000000	€/string	6	3.6	8.4
	high pressure air piping from well head to plant	10	km	1000000	€/km	10	6	14
grid connection	fields	2		3000000	€/field	6	3.6	8.4
	power line	25	km	1500000	€/km	37.5	22.5	52.5
gas connection	Gas under-station +pipeline	1		1000000	€	1	0.6	1.4
resulting CAPEX					**M€**	**280**	**168**	**391**
specific CAPEX		**300**	**MW**		**€/kW**	**932**	**559**	**1304**

The more detailed estimates by KEMA result in a higher cost range when compared to the literature cost range showed before in Table 7-1. The total plant investment cost is in fact around 930 EUR/kWe which is higher than 830 EUR/kWe (highest estimate) as given by literature. An uncertainty of +/- 40% is estimated at this stage of the design process. This results in investment costs of 560-1300 EUR/kWe that corresponds with absolute investment costs of 168-390 MEUR.

The pie-graph of Figure 7-1 gives a graphical representation of the cost breakdown of the CAES plant as estimated by KEMA. The compressor is the most expensive component due to the high pressure ratio and to the intercooling system. The second major cost component is the two-stage expander (turbine). The electric connection trough a power line represents a high cost in this case. This is because the CAES power plant is located at a long distance of 25 km (average) from the closest available electrical grid substations. As stated before, this will have to be reconsidered and discussed with TenneT in the further future.

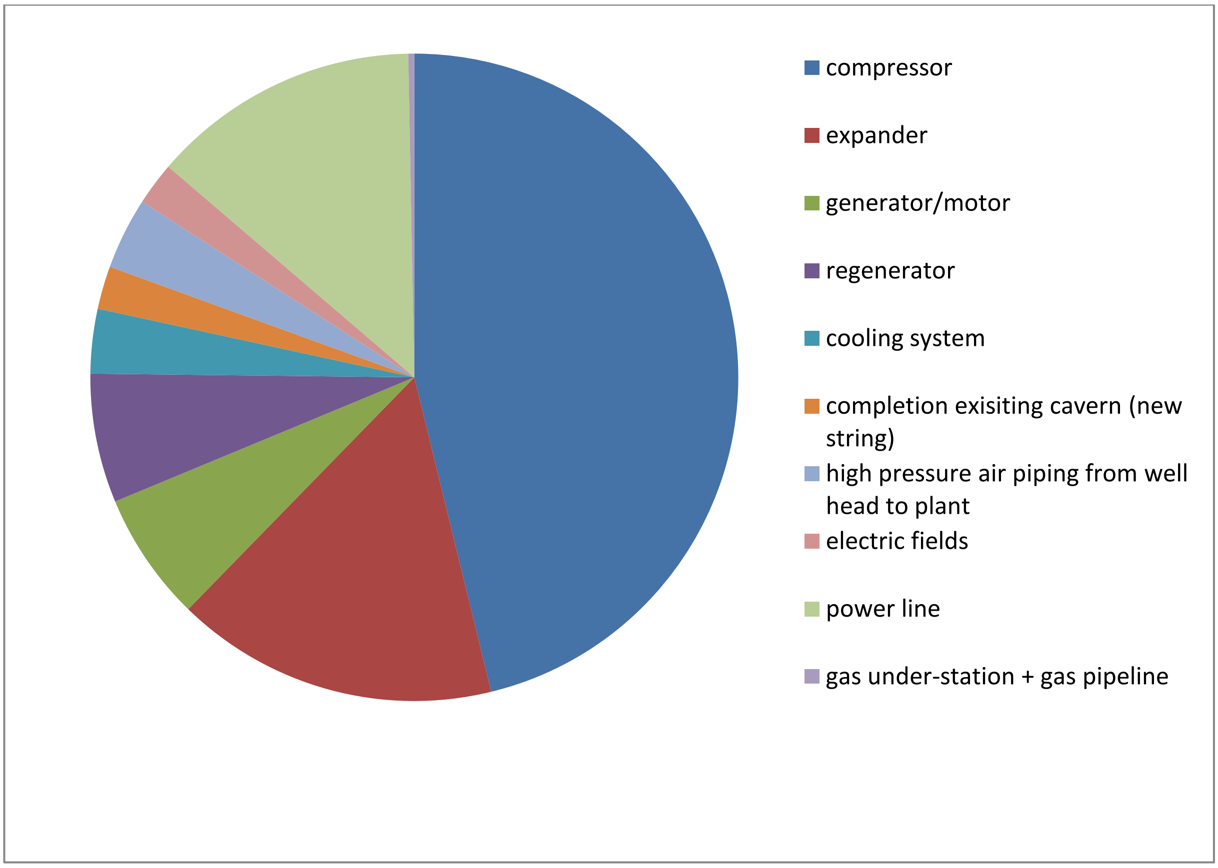


Figure 7-1 Pie-graph of the estimated cost-breakdown

The high investment costs for the compressor can be reduced by optimizing the plant design. When the plant is designed using a compressor that is half the size of the current compressor (and thus has to run double the time), the resulting base case investment cost would be reduced to approximately 215 MEUR (720 EUR/kWe).

When the cost of cavern creation have to be included in the estimation (like e.g. for the region of Drenthe), then the base case results in an total investment cost of approximately 340 MEUR (around 1100 EUR/kWe).
See table 7-3 and figure 7-2 for the 'Drenthe case', a CAES development at a new to develop cavern site.
Developing a new cavern at an existing site is, of course, less expensive due to the lacking of the necessity to develop a new site. When this 100 million Euro investment is substracted from the 'Drenthe case', the outcome is an investment of appr. 240 Million Euro (800 €/kW).

Table 7-3: CAES plant investment cost estimate, new cavern (in Drenthe)

part	component	amount	unit	specific cost	unit	base estimate (M€)	low estimate -40% (M€)	high estimate +40% (M€)
power plant	compressor	1		40,000,000	€	40	24	56
(component cost)	expander	1		15,000,000	€	15	9	21
	generator/ motor	1		6,000,000	€	6	3.6	8.4
	regenerator	1		6,000,000	€	6	3.6	8.4
	cooling system	1		3,000,000	€	3	1.8	4.2
	total installed cost					210	126	294
cavern development	completion exisiting cavern (new string)	1		6,000,000	€/string	6	3.6	8.4
	brine pipeline	1		50,000,000	€	50	30	70
	new drilling site	1		50,000,000	€	50	30	70
	high pressure air piping from well head to plant	1	km	1,000,000	€/km	1	0.6	1.4
grid connection	fields	2		3,000,000	€/field	6	3.6	8.4
	power line	11	km	1,500,000	€/km	16.5	9.9	23.1
gas connection	Gas under-station +pipeline	1		1,000,000	€	1	0.6	1.4
resulting CAPEX					**M€**	**341**	**204**	**477**
specific CAPEX		**300**	**MW**		**€/kW**	**1135**	**681**	**1589**

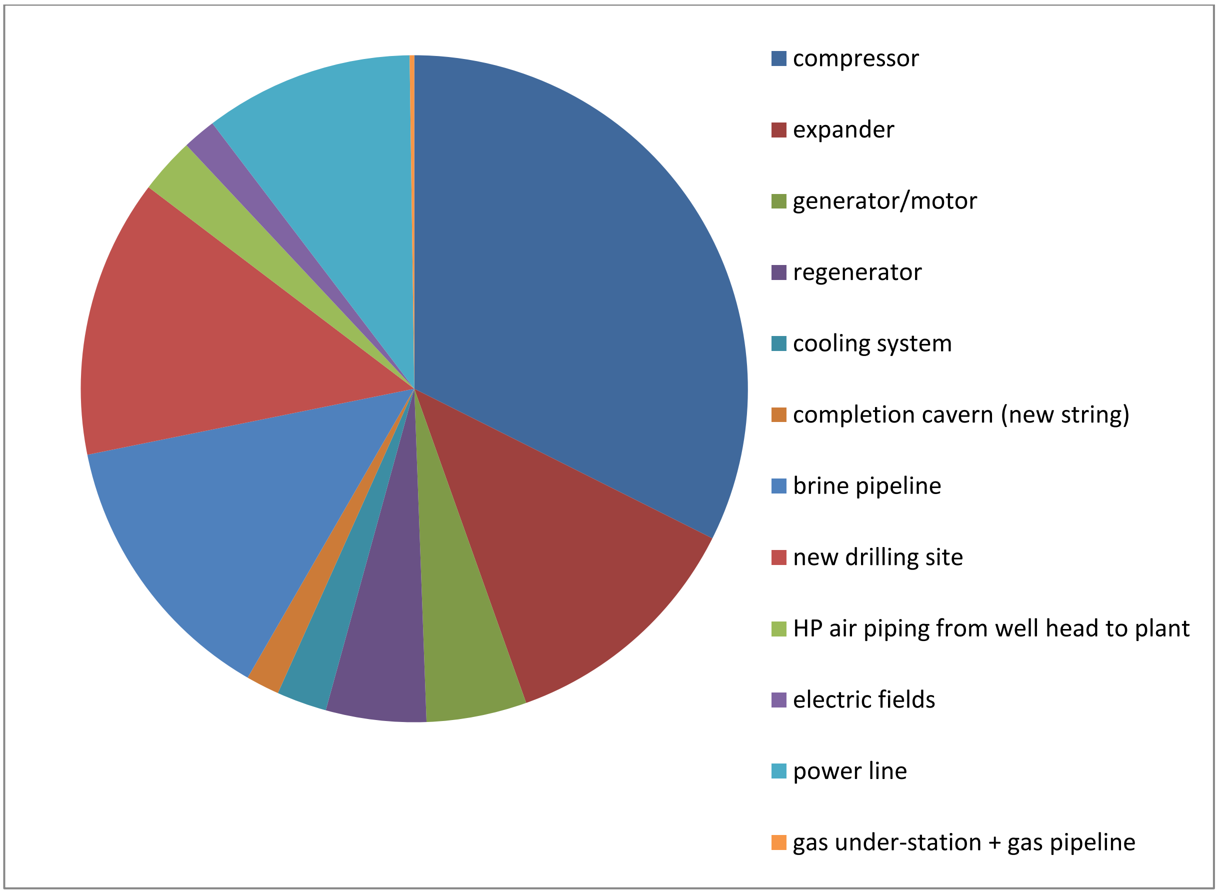


Figure 7-2 Pie-graph of the estimated cost-breakdown, new cavern site (in Drenthe)

8 VALUE ANALYSIS - YIELD AND NPV

8.1 Variable Costs

In operational terms a CAES is similar to a combination of a pumped storage unit and a gas turbine. A pumped storage unit generates electricity by charging and discharging electricity and a gas turbine generates electricity by burning gas. The combination, a CAES, charges with electricity and discharges while consuming gas.

A pumped storage unit charges when the electricity price is low and discharges when the electricity price is high. A pump cycle is optimized by maximizing the returns from a pump cycle while taking into account its pump efficiency, its storage capacity and the expected value of discharging later in time. Hence, the marginal pump cycle cost is the total of the generating variable operating and maintenance cost and the value of energy stored, which is equal to the electricity charging cost and the pump variable operation and maintenance cost. The marginal cost thus changes with the electricity prices and with changing operating conditions influencing its pump cycle efficiency.

A gas turbine is dispatched when the electricity price is higher than the marginal cost of generating electricity, which is equal to the fuel cost (including transport etc.), emission cost and its variable operation and maintenance cost. In addition there are start and stop costs which have to be off-set every start-stop cycle. The marginal cost changes with fuel and emission prices and with changing operating conditions influencing its fuel efficiency and start and stop costs.

The CAES marginal cost is a combination of cost factors found in a pump storage and a gas turbine, the main differences are the efficiencies and height of costs dealt with. Hence the marginal cost of production is determined by the following formula:

(1)

(2)

(3)

At maximum pump and generation capacity 176 MW of electricity is charged at time t_0 and 300 MW is discharged at time t_1 while consuming 341 MW gas. For every MW produced the net cost of electricity is therefore 1/1,7 times the electricity price when charging plus 1/0,88 times the gas price when producing. These efficiencies are conservative estimates and assumed constant in part load and across marginal pressure drops in the cavern. With the VO&M costs fixed at 2.3 EUR/MWh

and an emission rate of 57 kg/GJ, the remaining variables are a function of the scenarios and the market model.
As indication a simple example of the marginal cost has been worked out with the already mentioned information and the APX price on April 12, 2012 for Electricity of around 50€/MWh, Gas of around 25€/MWh and a CO2 price of 10€/ton.
For this example the calculated Marginal Cost is 62 €/MWh.
Note: Gas contributes very strongly to the marginal cost of CAES and these cost have to be made at the moment of electricity production. This will coincide with the moment of high energy prices. Thus, best way to optimize CAES is minimize the use of gas during energy production as is done in adiabatic CAES.

8.2 **Market Modeling**

KEMA models the market as a uniform cost-based auction, where market participants bid at the level of their short-run marginal cost. The market participants receive the market price that equates the total supply and demand in the auction. They are awarded sales exactly equal to the quantity of power that they can produce at a marginal cost less than or equal to the market price.

In practical terms this means that a generator would produce all power for which its marginal cost is less than the market price and it would not produce any power for which its marginal cost is higher than the market price. Because a firm sells its output at the market price and that market price is usually above the marginal cost of production cost of all or almost all the output it produces, the market price revenue achieved by the firm contributes to the coverage of its going-forward fixed cost of operation. If the contribution margin that a particular market participant receives is higher than its fixed cost, this is signal that the firm might be profitably expanded. Assuming that there are no barriers to either a new entry or existing firm expansion, large profits among generators would likely lead to entry of new firms and plants that would drive down prices and dissipate the highest profits. If the net revenue (after covering variable cost) is less than is necessary to cover the fixed costs for generation of the company, it is likely that this company will need to exit. When exit occurs, the supply curve in the industry shifts to the left and the equilibrium market price rise, so that all remaining firm earn higher prices and greater contributions to fixed costs[2].

The system marginal price is equal to the Short Run Marginal Cost (SRMC) of the last most expensive generating unit. The crucial assumption is that generators bid at SRMC. The SRMC

[2] Borenstein, Severin; Bushnell, James, (1999) “Market Power in Electricity Markets: Beyond Concentration Measures”, Energy Journal, 1999, Vol. 20 Issue 4, p65, 24p; Von der Fehr, N.-H. & Harbord,D., (1998) "Competition in Electricity Spot Markets. Economic Theory and International Experience," Memorandum, Oslo - Department of Economics.

consists of the variable costs of plant operation, made up of fuel and CO_2 costs plus variable operational and maintenance costs. Wholesale market price represented by SRMC of generation represents the market “bottom-line” and implies availability of sufficient capacity in the system and strong level of competition.

However revenue from such a cost-based auction may be insufficient to cover the generation average cost and ensure long-term financial viability market participants. Some energy economists argue against this position and allege that in the competitive markets, there is no need for additional price elements and market price should reflect the actual equilibrium between the demand and supply. However, a pure modelling of a wholesale market as cost–based auction excludes any price mark over SRMC of generation units. Therefore, there is a need to foresee an additional “price adder” that will reflect the capacity scarcity (“Capacity Premium”) in the system and replicate the effect of long run marginal cost (“LRMC”) pricing that should determine the market equilibrium in long run.

In longer-term, new capacity needs to be added to the system, as demand increases and old generation units retire. Generally, the most efficient new entry technology should recover their investment costs, depending on the reserve margin of the market[3].

8.3 Modeling Software

KEMA uses PLEXOS for Power Systems™ (“PLEXOS”) for this market modelling assignment. PLEXOS is a state-of-the-art generation optimization and price forecasting model. PLEXOS was specifically developed for the electricity industry and is a powerful simulation tool that integrates capacity expansion, generation dispatch, transmission flows, and pricing simulation with risk management, hydro, emissions and ancillary services dispatch. It has the capability to apply mixed-integer optimization for unit “on/off” decisions, respecting minimum up and down times and other dynamic operating constraints. It applies security-constrained unit commitment and optimizes the commitment with respect to transmission and generation contingencies. It can incorporate hydro systems, fuel and emission constraints as well as requirements for co-optimization of reserve.

[3] Should sufficient capacity be available, the market price will approach the producers’ short run marginal costs. Oppositely, the market price will start rising if the generation reserve margin is depleting and the probability to lose system load is increasing. In this case there will be a need to apply a “price adder” and adjust the system marginal prices.

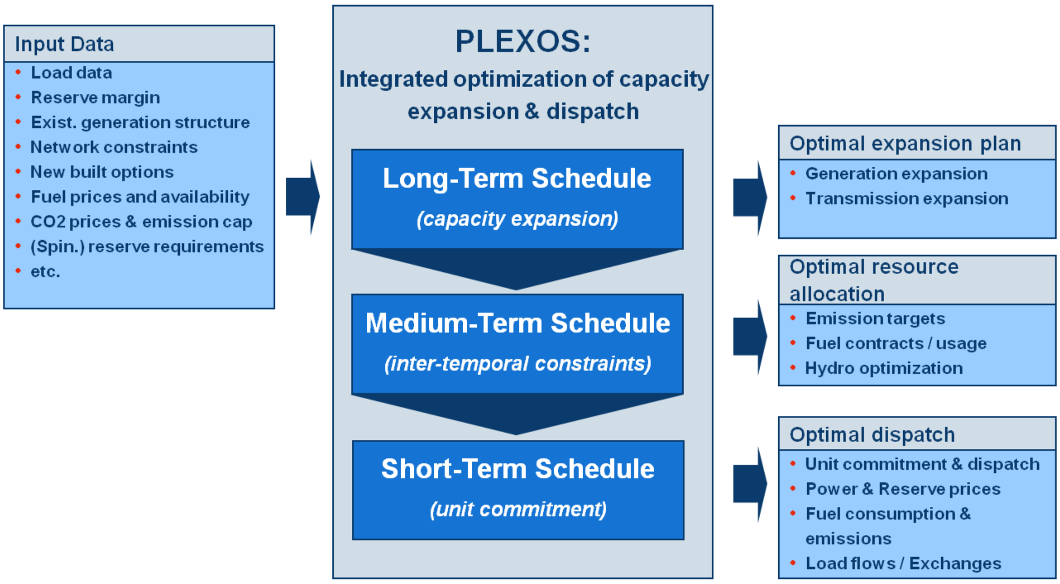


Figure 8.1 – Overview of PLEXOS modeling capabilities

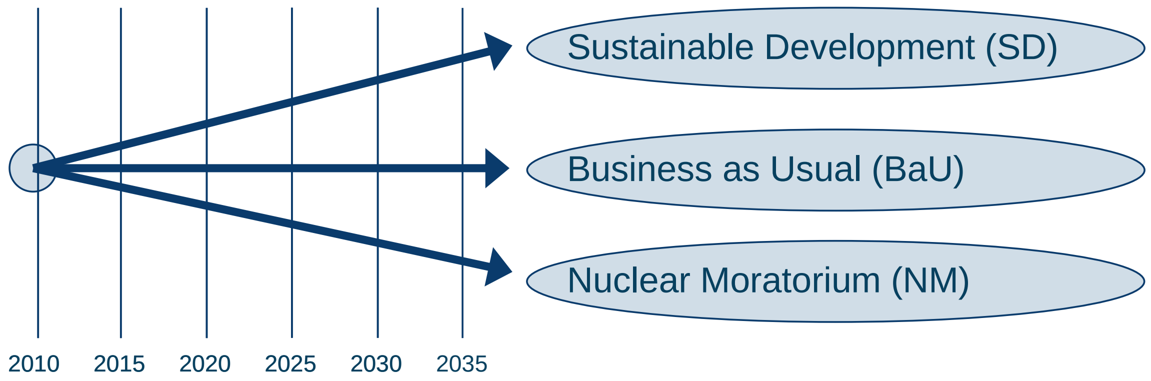
8.4 Background and description of Main Scenarios

KEMA has developed long-term market scenarios for the future North West European electricity markets. We have considered three market development scenarios for the years 2015, 2020, 2025, 2030 & 2035, for the power price drivers:

- Fuel & emission prices,
- Electricity demand,
- Installed generation capacities,
- Interconnectors.

The three scenarios are:

- "Business as Usual": this scenario describes a likely development of the electricity supply industry in Europe until 2035. The title "Business as Usual" implies that the future development will be in line with the developments experienced in the past.
- "Sustainable Development": this scenario is based on an assumed full implementation of the ambitious European environmental and climate policy goals. It is in particular based on the European 20-20-20 goals by 2020.
- "Nuclear Moratorium": this scenario takes into account the changed European public perception towards nuclear generation following the Fukushima event. The scenario assumes a fast nuclear phase-out.



The scenarios are calculated on an hourly basis. For 2013 a reference calculation was performed. In summary, the three modelling scenarios which KEMA calculates are characterized by:

Scenario Title	Scenario Description
Business as Usual	• The expansion of generation capacities will be based on the assumptions underlying the ENTSO-E security assessment forecast • Load and demand forecasts are based on usual TSO forecasts without consideration of (energy & climate) policy aspirations • Fossil fuel prices based on the IEA WEO 2010 "Current Policies Scenario"
Nuclear Moratorium	• No new nuclear generation beyond projects beyond point of no return • The expansion of renewable will be the same as in the base case scenario • Additionally needed generation capacities met by steam coal and natural gas • Load and demand forecasts are based on usual TSO forecasts without consideration of policy aspirations • Fossil fuel prices based on the IEA WEO 2010 "New Policies Scenario"
Sustainable Development	• The expansion of renewable will be based on National Renewable Energy Action plans • Additionally needed generation capacity additions met by steam coal and natural gas • Load and demand figures will reflect EU efficiency targets • Fossil fuel prices based on the IEA WEO 2010 "450 ppm Scenario"

The level of granularity for the calculations were differentiated between a core region comprising Germany, France, the Netherlands, Belgium and Luxembourg and satellite regions. The core region was modelled in much more detail than the satellite regions. In particular all power plant units above 100 MW_{el_net} were modelled individually, whereas the available capacities in the satellite regions are aggregated by fuel and technology according to the (future) fuel mixes in these countries.

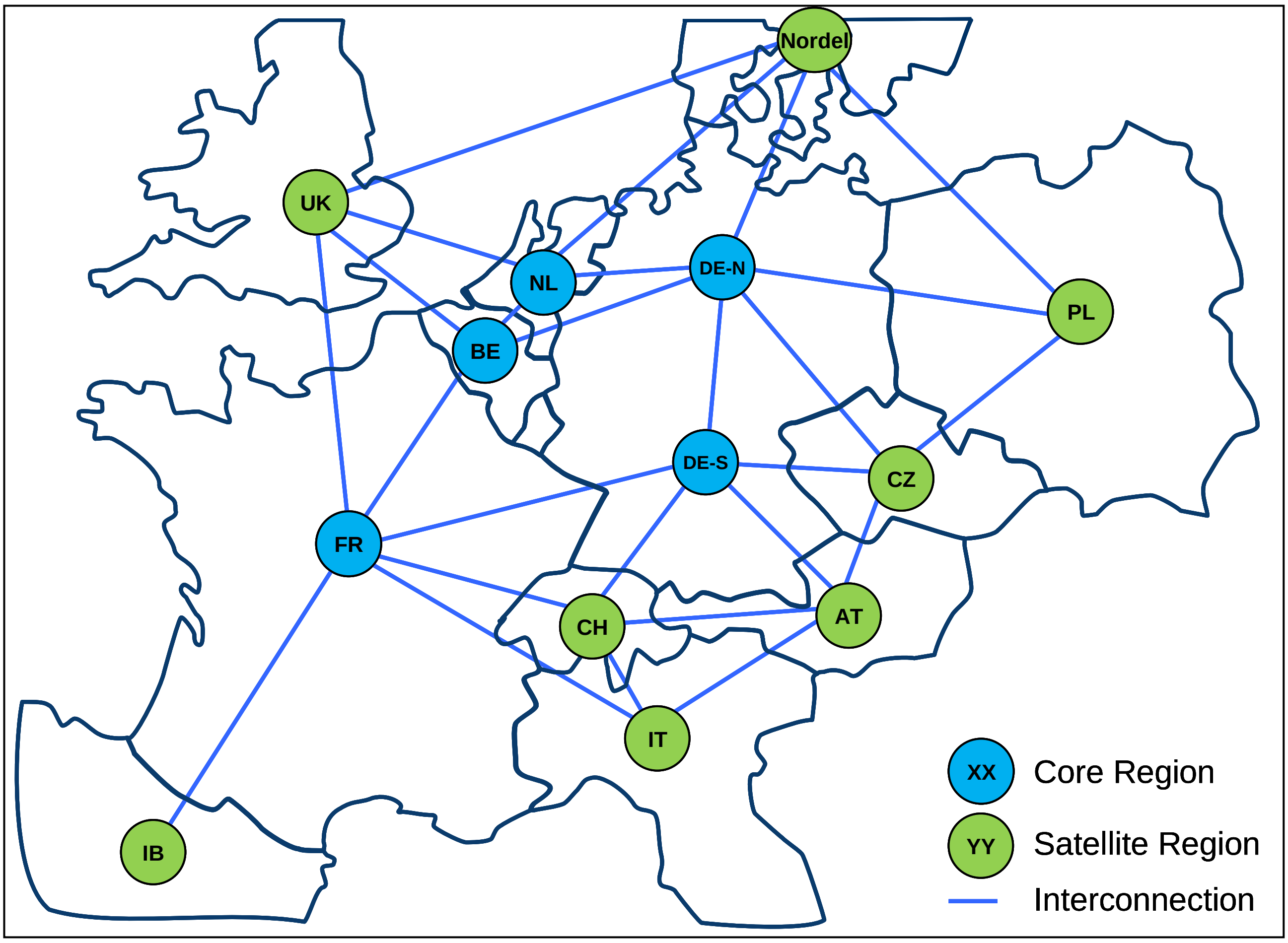


Figure 8.2: Definition of core and satellite regions
Source: KEMA

8.5 **Benefits**

CAES revenues are earned through electricity production for customers and by offering regulation and reserve power for the imbalance market controlled by the Transmission System Operator, TenneT. Electricity producing companies and / or their trading partners carry so called *Program Responsibility* (PR) requiring them to balance production and demand for their customers per fifteen minutes.

Endex is a platform for long term trade and the APX is the platform for day-ahead and intraday trade. PR parties can trade until two hours before execution after which TenneT takes over by operating on the imbalance market. Imbalance is settled at an imbalance price different from APX prices. The imbalance market includes *Regulation and Reserve Power* (RRP) to restore large deviations in the overall system balance. These markets are supplemented by primary control, which is an automated obligatory response for large generators and for which no market exists. TenneT can also contract Emergency power but this is generally contracted on a bilateral basis for which no clearing platform exists.

Time Scale		
Days / Hours / Quarters	Quarters / Minutes	Minutes / Seconds
Program Responsibility • PR parties maintain the balance between customer demand and production • Deviations are settled on the imbalance market	**Regulation and Reserve Power (imbalance market)** • RRP controlled by TenneT in single buyer market • Bid obligation for units >60 MW	**Primary Control** • Locally at the generator • Obligatory for large units • Automated response • No settlement and no market.

8.5.1 Spot Market

Taking into consideration the CAES compressor and expander capacities and the volumes that can be stored in the reference cavern design, the CAES is able to charge or discharge a full capacity for about 8 hours straight. Hence, the CAES is dimensioned to operate based on daily price fluctuations in the power markets. These price fluctuations are related to the forecasted electricity demand and the operating cost of the marginal production unit on an hourly basis. Future price levels will therefore change according to the overall generation fuel mix and prevailing fuel and emission prices.

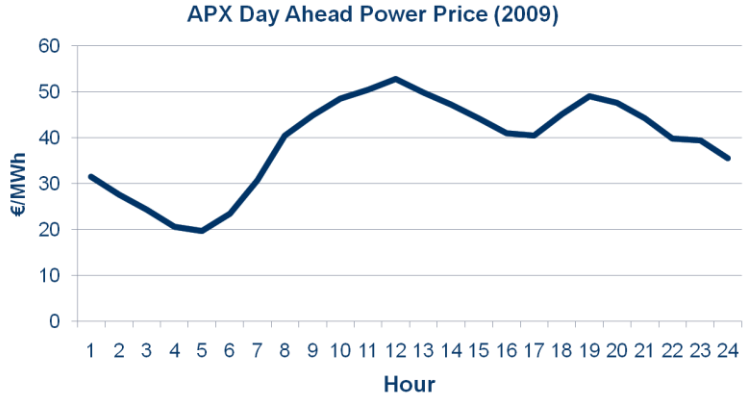


Figure 8.3 – Example of the daily price fluctuations in the Dutch spot market for power (APX 2009 Average Day Ahead Power Prices).

Modeling with PLEXOS simulates the optimal dispatch of power plants under to the scenarios proposed above, leading to a price curve similar to APX prices. The CAES is dispatched according to the system electricity price by charging when the price is sufficiently low and discharging when the price is sufficiently high. The dispatch is a co-optimization taking into account the marginal cost price, storage capacities and other market variables along with an optimization of the reserve markets.

8.5.2 **Imbalance Market**

Imbalance is the result of forecasting errors and sudden changes in production or demand e.g. when a generators fails. Large generators (>60 MW) are obliged to offer regulation and reserve power to ensure that TenneT can dispatch enough power to restore the system balance even when the largest generator in the systems fails. An example of the imbalance control signal indicating the required Regulation and Reserve Power is shown in Figure 8.4.

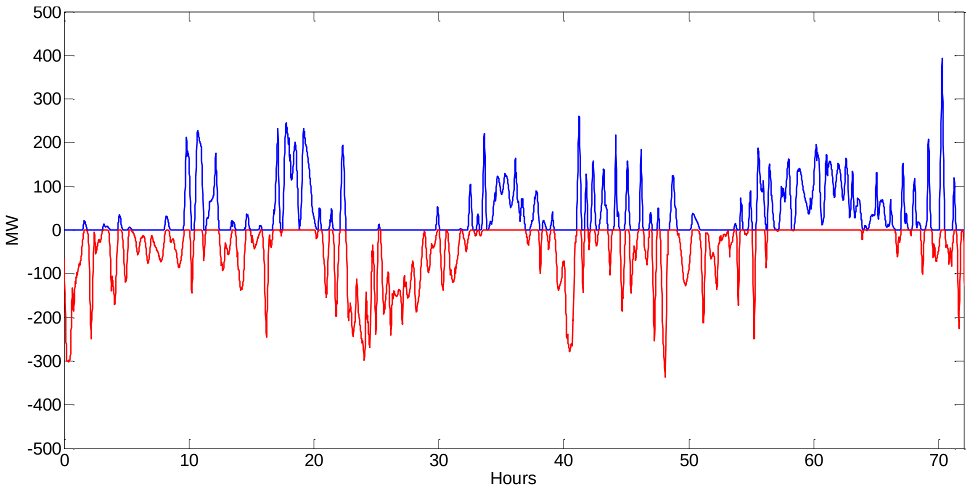


Figure 8.4 – Example of the system imbalance control signal indicating the need for Regulation and Reserve Power for balancing operations by TenneT TSO.

The advantage of a CAES is that with both a charging an discharging capability it can offer both down and up reserve, hence providing a service to TenneT when there is a system surplus or shortage. Especially when there is a system surplus (e.g. in a situation with high wind at night when a 'must run' unit cannot provide enough downward reserve) while the CAES is offering downward reserve the CAES can charge at very low or negative prices when dispatched by TenneT.

In the future, increasing amounts of intermittent resources in the system (e.g. wind and solar power) increase the need for RRP because of the high variability and limited predictability of power output. This will partly be reflected by an increased need for (tertiary) reserve controlled by TenneT, but will mostly be covered by PR parties increasing the flexibility in their generation portfolios available for intraday trade via the APX. Intraday trade clears already a large share of the imbalance present in the system. Hence, the size of (tertiary) reserve in the regulation and reserve market controlled by TenneT will increase, but because there is an imbalance cost risk for the PR party, it has an incentive to also increase its internally maintained (hourly) reserve significantly when it increases wind power in its portfolio. The reason is that PR parties have an incentive to reduce the imbalance to avoid high costs charged by TenneT. The assumptions on the size of regulation and reserve markets are provided in Table 3.

Required Imbalance Reserve Capacities (MW)	NOW 2011	BAU / NM 2035	SD 2035
NL Hourly Down	800	1461	5000
NL Hourly Up	800	1461	5000
NL Regulation Down	350	350	350
NL Regulation Up	350	350	350
NL Reserve Down	200	326	1000
NL Reserve Up	200	326	1000
Installed Wind Power	**2400**	**6000**	**24000**

Table 3 – Assumptions for the future required reserve volumes

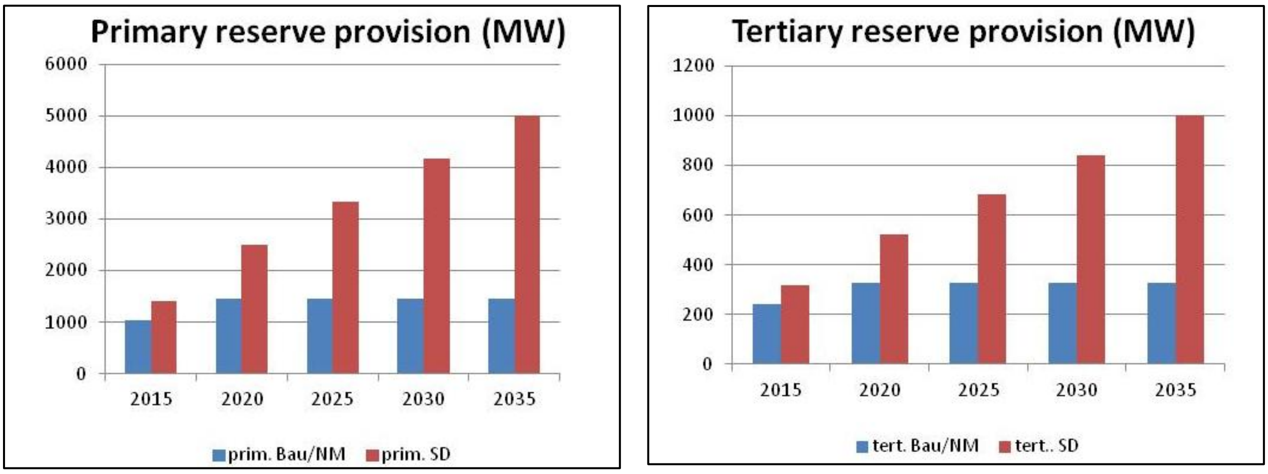


Figure 8.5 – Reserve requirements per year: SD scenario requires strong growth

Please notice that in the SD scenario, the amount of wind energy is very high, largely caused by offshore wind. This in turn requires high reserve capacities to cover potential grid imbalance. In Plexos, the amount of reserve is given in as a fixed number, accounting for the imbalances that may occur given the (known) variations in available wind power. There are no time series involved with forecasting errors.

The prices and turnover of the market for RRP in recent years are shown in Figure 8.6. The assumption for the future is that there are no changes in the regulation regarding the provision of RRP and that the reserve markets as defined above are adequate for system reliability. The maximum reserve provision per generator in each of the reserve markets is provided for in
Table **4**.

The RRP markets are co-optimized with the dispatch in PLEXOS and the reserve price is the shadow price for providing RRP in the Dutch market. An analysis of the Business-as-Usual scenario without regulation and reserve provision is presented as well. the amount of required reserve is a fixed input, depending upon the amount of intermittent resources in the system. After

2020, only the reserve requirements in the SD-scenario grow. The reserve requirements in the other scenarios remain the same after 2020.

Reserve Provision as a percentage of Max Capacity				
		Primairy reserve	Secondary reserve	Tertiary reserve
COAL	**ST**	**5%**	**10%**	**10%**
GAS	**GT**	**15%**	**50%**	**100%**
GAS	**CCGT**	**8%**	**50%**	**50%**
Uranium	**ST**	**5%**	**10%**	**10%**
CAES	**PS**	**5%**	**50%**	**100%**

Table 4 – max reserve provision per technology for different reserves.

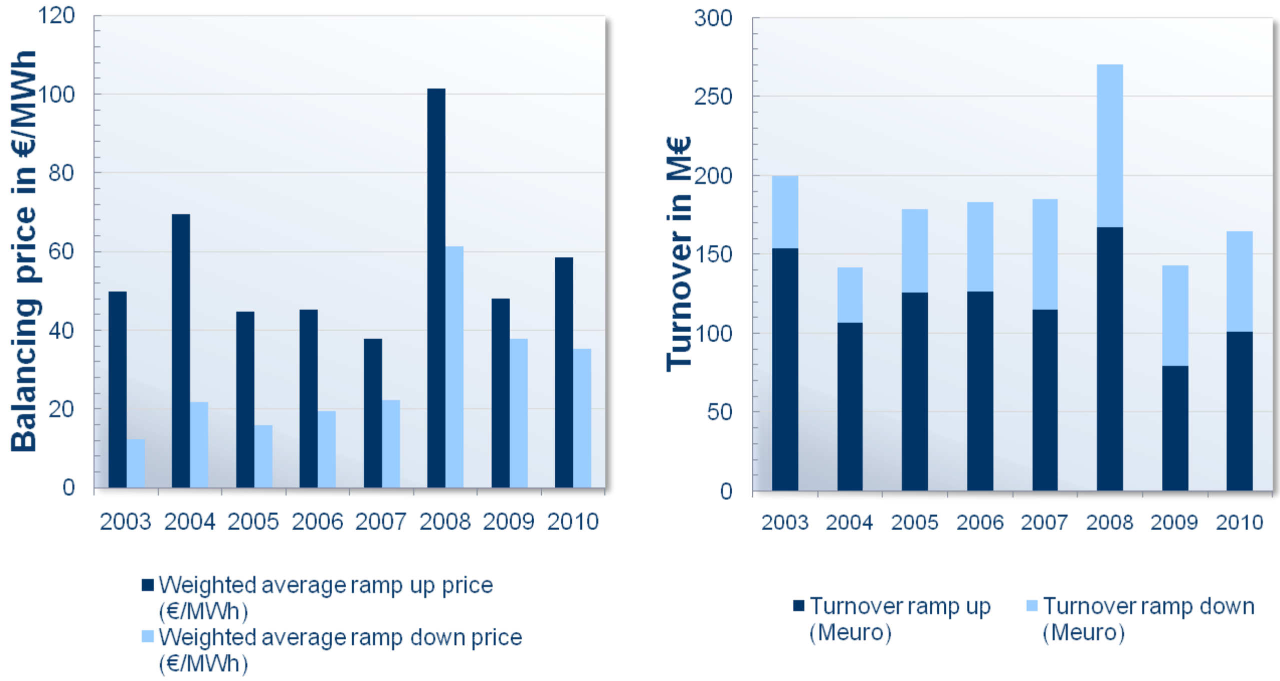


Figure 8.6 – Historic imbalance prices and total turnover.

8.5.3 Modeling Results

Using the inputs described in previous paragraphs, KEMA calculated the resulting electricity prices in the scenario's mentioned, for each individual year 2015-2020-2025-2030-2035.

For each hour, the bid price ladder is calculated and the resulting electricity price is determined for a certain demand value. Imbalance is not determined as such, but the cost of (spinning) reserve is calculated in the system. The interconnection limitations are considered in the calculations as well, transport costs are not included.

Electricity prices are increasing significantly in the BaU and NM scenario, due to strongly rising gas prices. While the nuclear phase out initially leads to higher electricity prices this is offset by somewhat higher fuel prices in the BaU scenario in later years (see figure 5). Since the share of gas fired capacity is still fairly high in comparison to other countries the Netherlands remains a net importer in these scenarios (figure 6).
In the SD scenario, however, the strongly increased penetration of renewable resources in the fuel mix make electricity prices fall down hard. In the Plexos model this even leads to average negative prices in the Netherlands in 2035. This implies that these output calculations **cannot be used** for NPV calculations: markets will respond to decreased price expectations and influence market mechanisms, subsidies, PPA's and investments. A strong increase in wind power will result in a net power exporting position for the Netherlands (See figure 6).

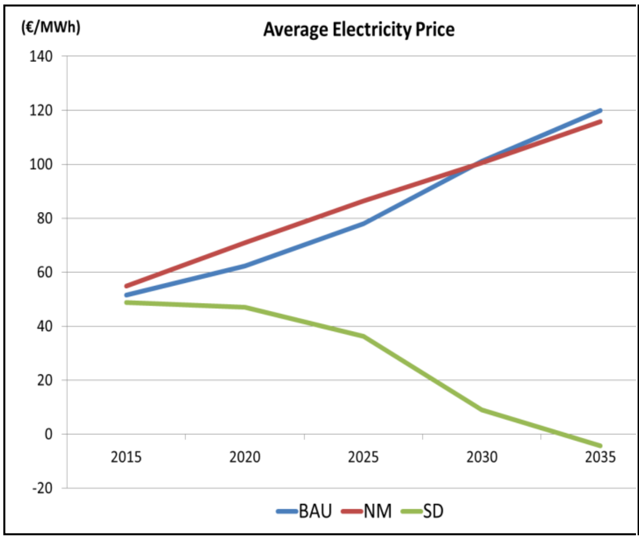


Figure 7 – Average electricity prices in the Netherlands per scenario

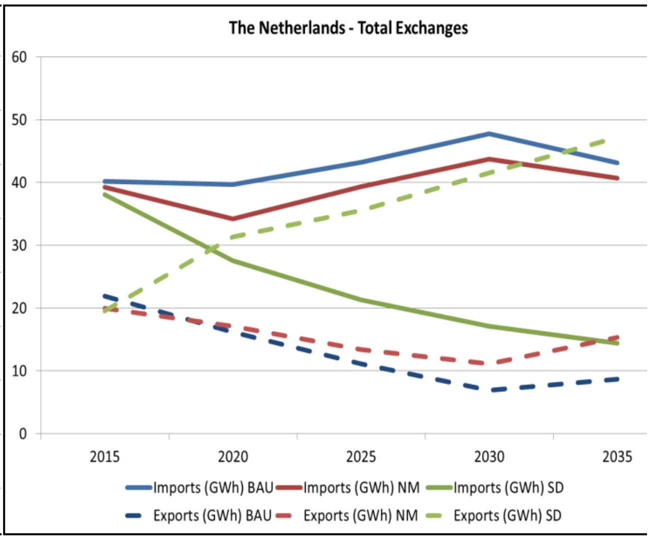


Figure 8 – Total import and export in the Netherlands per scenario

As mentioned earlier the dispatch of CAES is mainly influenced by the daily fluctuations in the electricity price. The price difference between peak and off peak prices should offset the operational cost, fuel cost and emission cost and leave a profit margin from production. Because the CAES produces more electricity than it takes from the grid the price delta required is lower than the Short-Run Marginal Cost. KEMA has made an overview of the price differences between peak and off-peak hours, starting from the largest price difference till the lowest difference. For every two hours of the day with a price difference larger than this required price delta, dispatch of the CAES is profitable.

While daily fluctuations in the price are larger in some days it is shown in Figure 7 that on an average day in each of the years per scenario the price fluctuations are **insufficient** for normal operation. Only in the extreme SD scenario daily price differences start to approach the required price delta in the final year of the explored time horizon. As stated above, the 2035 SD situation cannot be considered representative.

APPENDIX III shows what the dispatch and reserve offering pattern looks like summarized for an entire year, 2025 in the BAU scenario. It can be observed that dispatch is hardly profitable and hence even in peak hours the CAES unit is not dispatched more than 100 days in total even though it follows the pattern in daily price fluctuations nicely.

It does however still offer a lot of downward reserve power at night because all electricity it can store while being called upon in the reserve markets can be offered on the market in peak hours. Offering downward reserve can therefore lower the threshold for operating in the generation spot market.

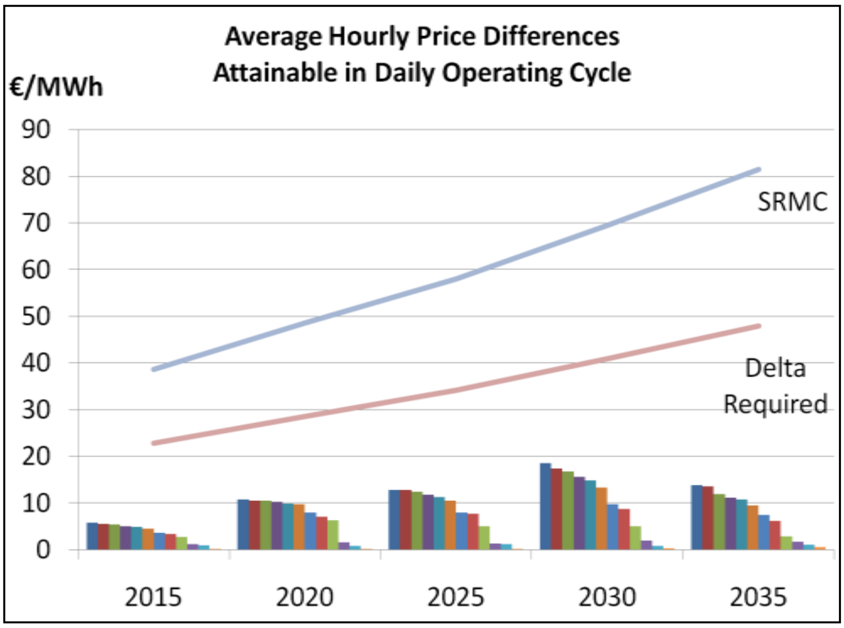
Average Daily Price Fluctuations by the hour - bars represent daily price differences in each scenario per evaluated year. For each year the left bar corresponds to the maximum average price difference and the right bar to the minimum average price difference for all days that year (often close to 0). This is compared to the CAES' SRMC and the Price Delta Required for Dispatch. The red line (Delta Required) is lower than the blue line (SRMC) because the CAES produces more energy (300 MW) than it takes from the grid (176 MW) when charging. Hence the required price difference between charging and discharging is lower than the SRMC. The required price delta is reflected by the red line. The red line does not intersect with any of the bars meaning that on an average day the price differences are insufficient for dispatch. Therefore the revenues from production are only positive in days with exceptionally high price fluctuations. SO CAES needs much higher differences between peak and off-peak prices. Moreover this is required to offset marginal cost. For investment even more price difference is required.

If the delta is zero, the marginal costs of CAES are equal to the price difference between peak and off-peak prices and the CAES will be dispatched. This however does not mean that the investment in CAES is justified since the earnings at the intersection are just zero. The difference between peak and off-peak prices needs to be larger during sufficient hours of the year for a reasonable pay back time. The extra delta is in the order of magnitude of about 25 EUR/MWh. It is not expected that in the future such differences will appear on a regular basis. Moreover several developments may point towards a direction where the differences are smaller. Increasing cost of CO_2 will reduce the difference between coal based and gas based electricity and therefore between peak and off-peak prices. Extra renewable energy may also lead to smaller differences than expected based on fuel prices alone.

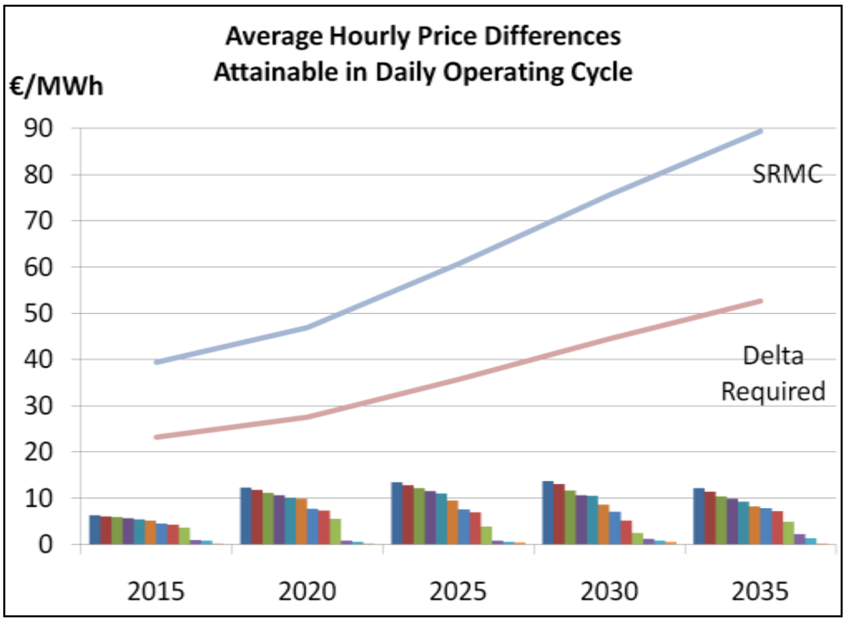
Already now peak prices are under pressure during sunny days due to the large amount of PV cells in Germany. In general wholesale prices tend to be lower due to the increasing amount of wind and solar. Dependent on the timing of the low (or even negative prices) this may be good or bad for storage. In the end however the present market model which energy oriented may not hold. Prices in general will be and already are in some countries too low to attract investment in new capacity. For the Netherlands this is not an urgent problem due to many new plants coming on line but in other countries discussion around capacity remuneration is already ongoing.

In order to earn enough money from arbitrage between peak and off-peak hours larger differences (deltas) are required than shown from our simulations. It is not expected that under future market circumstance such deltas will appear on a regular basis.

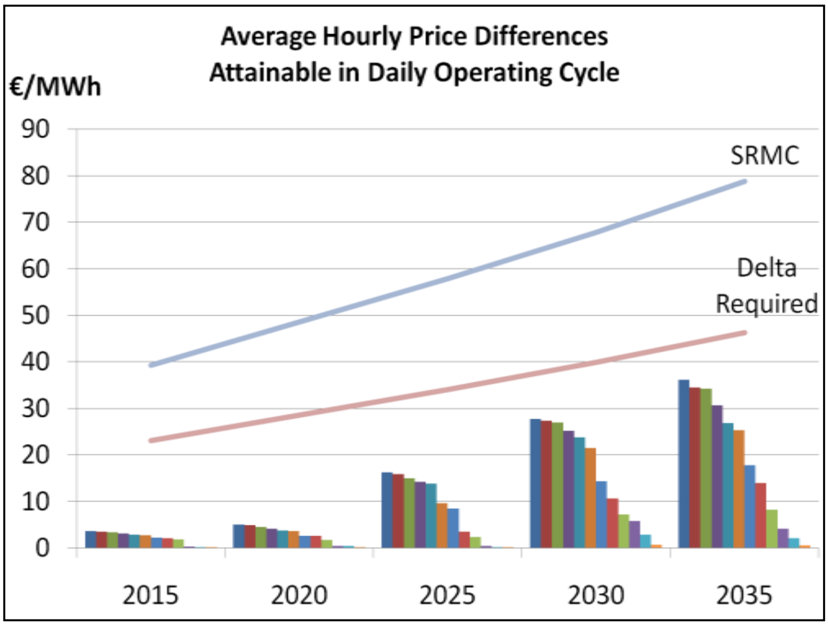
CAES plant has an estimated 2.28 EUR/MWh Variable Operation & Maintenance (VO&M) charge, which is higher than the average gas-fired power plant in the Netherlands (1.4 EUR/MWh). On average, power generation with a (Combined Cycle) Gas Turbine (CCGT) is preferred before generation with CAES. Reducing the VO&M charge may lead to an increased deployment of CAES.



Figuur 7a daily fluctuations, Business as Usual



Figuur 7b daily fluctuations, Nuclear Moratorium



Figuur 7c daily fluctuations, Sustainable Development

8.5.4 Comparison of the CAES' performance in each of the scenarios for the years evaluated.

KEMA has also calculated the use of CAES as both a spot market unit and a reserve market unit. The fluctuations in demand rise from failures in power plants, as well as from wind power.

The results show that revenues from generation dispatch (spot market) are close to zero or negative in most years across all scenarios. The revenues of the reserve markets exceed the generation revenue by far and are only partly offset by the pump costs made. Hence the net profit is mainly determined by the reserves revenues.

Revenues in all scenarios are largely determined by the revenues from the reserve market. From 2015 onwards, the size of the reserve market in the SD-scenario is bigger than in the other two scenarios (Bau and NM). This difference in size (primary and tertiary reserve markets) between the SD and the other two scenarios increase over the years. The reserve requirements in the BaU and NM scenarios remain equal from 2020 onwards, whereas the requirements in the SD-scenario keep growing. This results in a strong increase in revenues for CAES, which is able to supply such reserves.

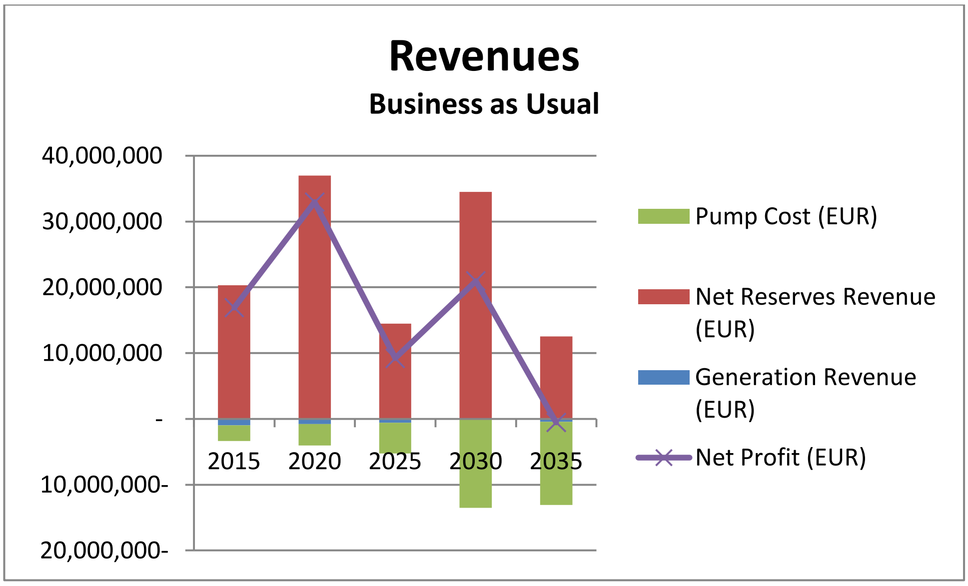


Figure 9a CAES financial performance Business as Usual

The reserves revenues and net profit are developing in a non linear fashion. There are several possible explanations.

In the NM scenario, nuclear capacity in Germany is completely phased out in 2025. In 2030, this capacity is largely replaced by gas-fired power plants that provide (spinning/primary) reserves and in turn replace (part of) the reserves (and the accompanying revenues) provided by CAES in the BaU scenario.

From 2025 in the NM scenario, CAES is more often deployed for (unprofitable) generation with the aim of maintaining system stability, but resulting in relatively high 'pump costs' for CAES and resulting in greater losses in the NM than in the BaU scenario.

It takes considerable time to dive into the model to see what the precise origins of the variations are.

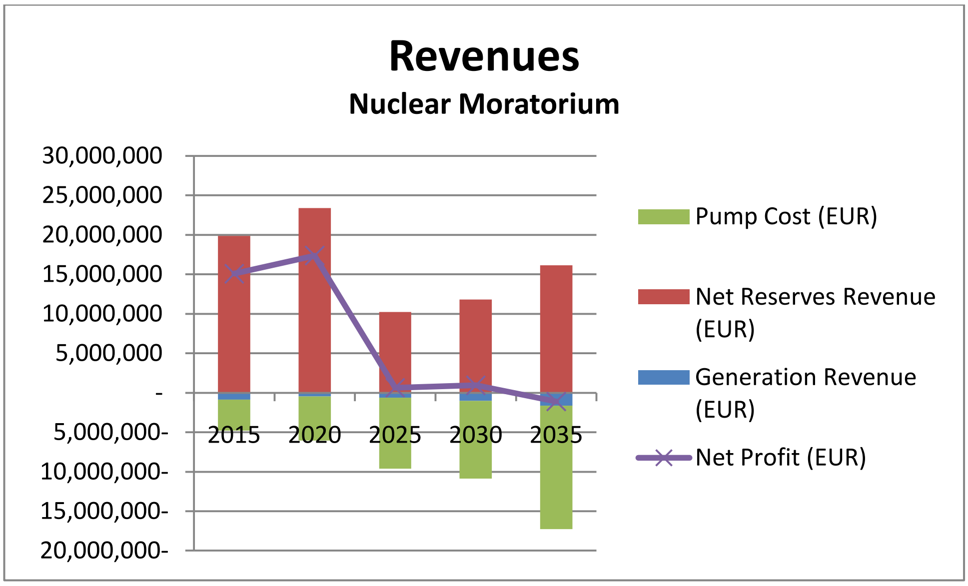


Figure 10b CAES financial performance Nuclear Moratorium

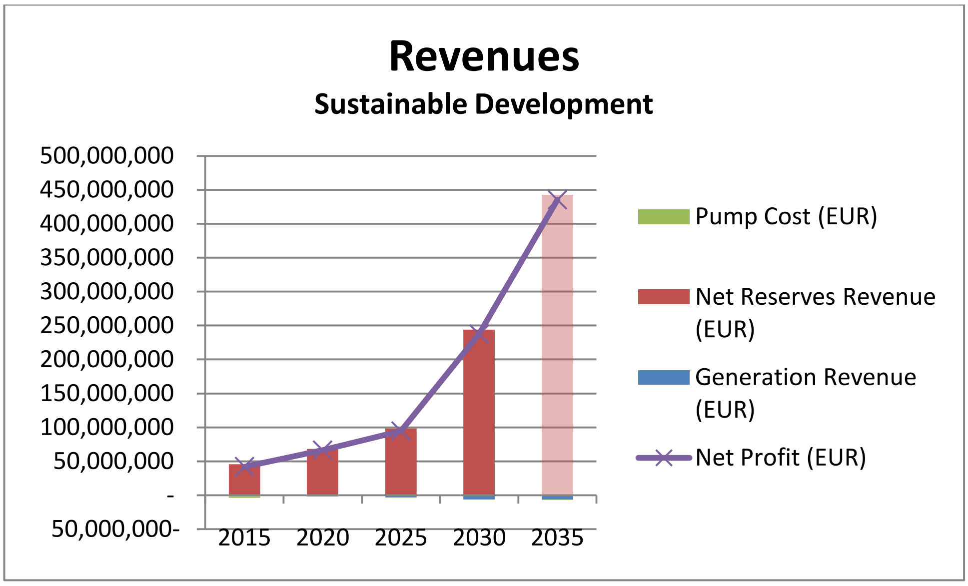


Figure 11c CAES financial performance Sustainable Development; results in 2035 must be ignored

CAES acts as a certain “emergency unit” that provides balancing power when it really is required. There is no fixed (daily) pattern for it. Ramp rates are steeper for CAES than for (CC)GT’s, which means it has an advantage in the very short term. Depending on the scenario, the capacity factor of a CAES plant is between 1 % (equals some 90 hours) and 8% (equivalent of some 700 hours), with emphasis on the winter months.

Lowering the variable cost (Short Term Marginal Cost) of CAES would improve its position in the merit order. Yet, Combined Heat and Power plants (CHP) which are already up and running, will often prevail in offering reserve power.

As mentioned above, further increase of RES disturbs the business case of new capacity under the present market model. It is expected that a new market model needs to be introduced probably based on energy and capacity remuneration (additional capacity payment of capacity mechanism or market). Under such a new market, capacity is often valuated at the cost of an OCGT. This would mean that more than half of the investment of the CAES would already be compensated by the capacity payment. This would throw a new light on the feasibility of the CAES.

How the balance would end up depends on the new market design and the height of the possible capacity payment. The CAES would maybe operate differently under the new circumstances so costs and benefits would need to be determined based on additional simulations. Complicating factor is that the optimum fuel mix will also change with increasing share of RES. Base load capacity would not run the normal 7000 hours but (much) less. Probably more intermediate and peak load capacity will give better overall results.

8.6 Net Present Value

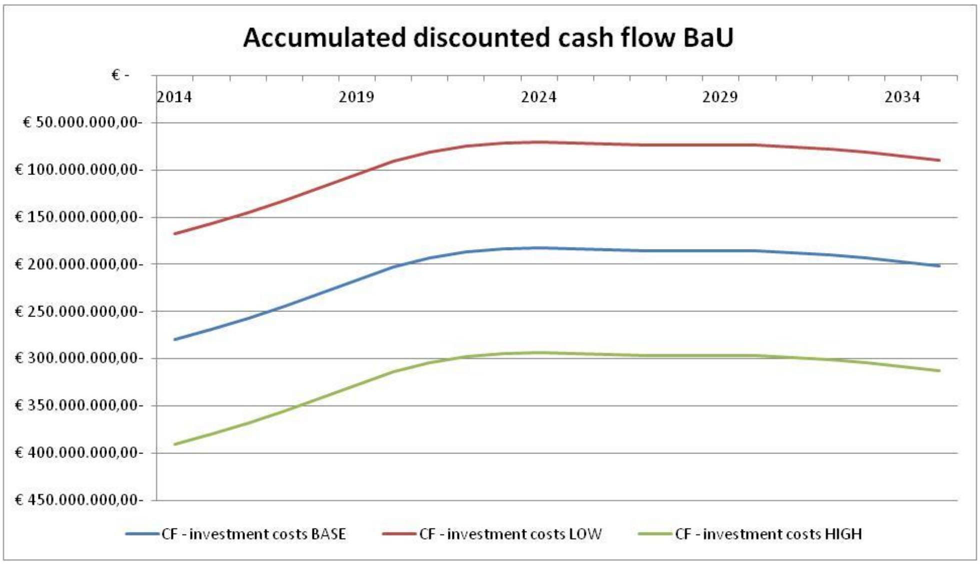
The investment value for a CAES plant has been estimated at 280 M€, plus or minus 40%. These investment values have been used with the revenue calculations, to calculate the net present value (NPV) of a CAES plant. An economic lifetime of 20 years and a weighted average cost of capital (WACC) of 10% have been assumed.

Investment and Net Present Value (M€)

	pessimist	base case	optimistic
investment	-391	-280	-168
Business as Usual	-313	-202	-90
Nuclear Moratorium	-400	-289	-177
Sustainable Development	439	550	662
Sustainable Development – after 15 yrs	128	239	351

Only in the case of the Sustainable Development scenario there is a positive NPV after 20 years of operation. Even when the plant can be realized at low investments, it still is insufficient to realize a positive NPV.

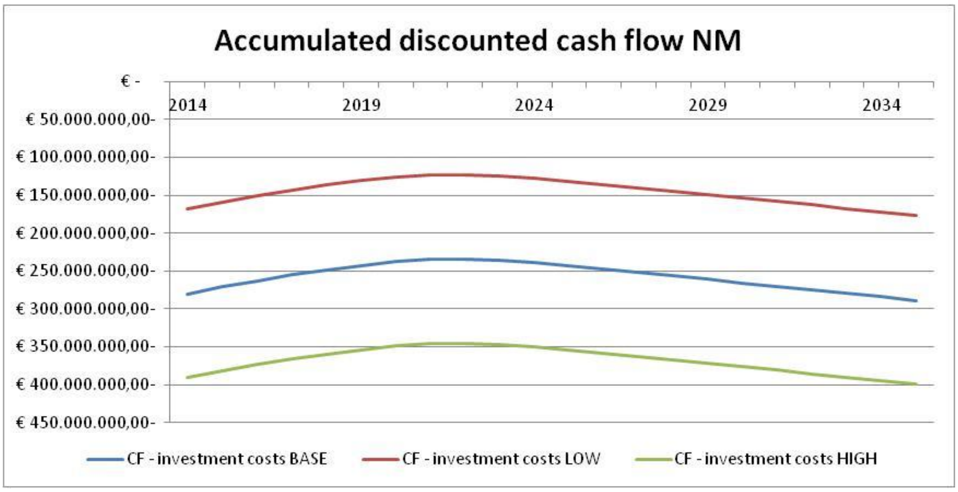
Business as Usual



The investment cannot be recovered during the first 20 years of operations, even considering the lowest investment cost. The income rises until 2020, but then starts to fall.

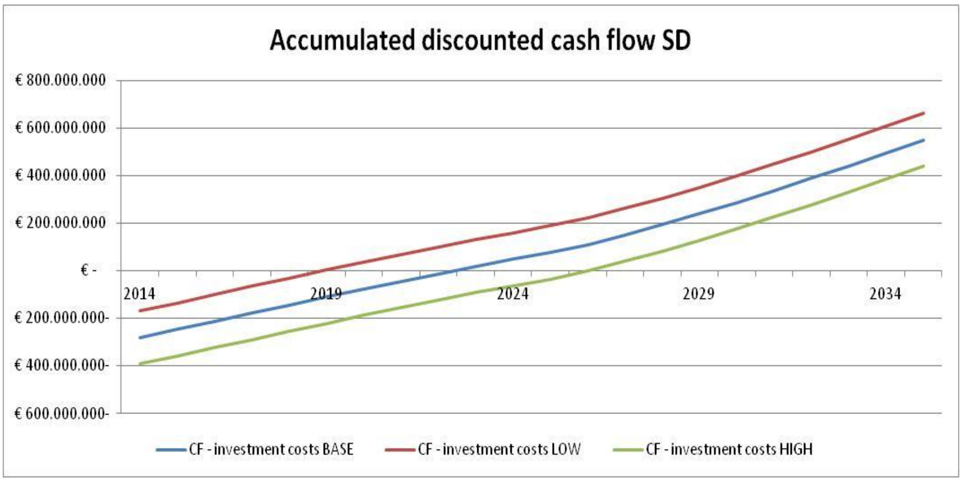
Nuclear Moratorium

The investment costs cannot be recovered during the first 20 years of operation. The revenues generated are positive during the first 10 years, but get close to 0 after 2025.



Sustainable Development

Given the very high revenues in the SD scenario, even the highest investment costs can be recovered within 15 years. As stated earlier, the income of CAES in the last period should be neglected.


Accumulated discounted cash flow SD
€ 800.000.000
€ 600.000.000
€ 400.000.000
€ 200.000.000
€ -
€ 200.000.000-
€ 400.000.000-
€ 600.000.000-
2014
2019
2024
2029
2034
CF - investment costs BASE
CF - investment costs LOW
CF - investment costs HIGH

8.7 Conclusion

- KEMA has modeled a CAES plant in a large scale simulation of the European power system, in order to determine the expected dispatch of CAES under current and future market conditions. Plexos simulation software has been used.
- Three scenarios for demand and supply have been studied.
- The model outcomes for Sustainable Development in 2035 cannot be used immediately, since the results seem to violate market principles and therefore will not be reached.
- Two markets for power have been taken into account for the Netherlands: the spot market and the reserve or imbalance market. Operating on these markets simultaneously is possible in a limited way; the simulation software used is able to find the optimum market operation.
- KEMA made no assumptions for other types of storage or technologies to absorb power fluctuations (considering e.g. more pumped hydro in Norway).

- Daily electricity price fluctuations on the spot market are insufficient to support economic operation of CAES in every scenario until 2035. The day-night differences in power price will remain limited in the Plexos model outcome, even in a Sustainable Development scenario. A CAES plant is therefore expected to be dispatched only occasionally and mostly in partial load.
- Based on the Plexos model outcome, the income generated by CAES from arbitrage ofspot market prices is too low to justify investments in a CAES plant. It is not expected that future market circumstances would provide sufficiently higher spread between peak and off-peak prices.

- The reserve market offers much more income and profit in all scenarios. Planning of the CAES operation will be less clear, but in general, night time storage and day time delivery will be standard.
- CAES is especially suited for absorbing power in case of negative power prices, which may happen with large growth of (offshore) wind penetration. Regardless of the operating market chosen.
- Revenues from the reserve market are especially high in the sustainable development scenario, in which a very high amount of reserve power will be required to accommodate rapidly changing wind output. Based on the Plexos outcome, the revenues of CAES in a SD scenario are expected to be 5-10 times higher than in the BaU/NM scenarios. The revenues in 2035 are ignored.
- CAES revenues could increase if the operational cost would be reduced and would equal the CCGT operational cost. This would improve the merit order position.

- Based on the Plexos model outcome, income generated through both spot and reserve market can support a business case in the Sustainable Development scenario. Income generated in the Business as Usual and Nuclear Moratorium scenarios (10-20 million euro per year, but getting lower towards 2035) is rather low to support a business case.

- However, revenues based on the reserve market are very sensitive to assumptions with regard to expected reserve requirements and reserve provision per technology, as well as policy and strategies defined in individual countries, TSO’s and throughout Europe. Possible future capacity market or mechanisms for instance will provide extra income for the CAES but may also have substantial influence on the reserve prices and the expected income from reserve markets.

9 PERMITS/VERGUNNINGEN

Since Permitting is based entirely on the Dutch rules and regulations, we have chosen to present our results and findings in Dutch.

9.1 Vereiste vergunningen

Er zijn diverse vergunningen vereist voor het realiseren van CAES (zie Bijlage A). Een aantal van deze vergunningen zijn in ieder geval benodigd, andere vergunningen zijn nodig afhankelijk van de specifieke locatie en omstandigheden van het project.

Voor alle activiteiten in de ondergrond geldt het vergunningenstelsel van de Mijnbouwwet, met name met betrekking tot opsporing, winning, opslag. Het zal duidelijk zijn dat voor bestaande cavernes de eerstgenoemde twee vergunningen niet aan de orde zijn. Een opslagvergunning zal echter hoe dan ook noodzakelijk zijn voor het CAES project.

Voor de bouw en de aanleg van de bovengrondse faciliteiten is de omgevingsvergunning in het kader van de Wabo algemeen verplicht. Deze vergunning omvat ook de vergunningen/of ontheffing ingevolge de Natuurbeschermingswet en de Flora en faunawet, indien er nadelige effecten zijn voor nabije natuurgebieden en/of beschermde planten- en dierensoorten. Dit is sterk afhankelijk van welke projectlocatie met bijbehorende infrastructurele aansluitingen wordt gekozen.

Verder is te verwachten dat een watergunning ingevolge de Waterwet vereist zal zijn. De Waterwet regelt uiteenlopende aspecten als grondwateronttrekking (bijvoorbeeld tijdens de bouw en aanleg), lozing op oppervlaktewater (bijvoorbeeld van gezuiverd afvalwater of koelwater) of werkzaamheden bij waterwerken (bijvoorbeeld kruisingen van watergangen).

Voorts moet in geval van substantiële grondontgravingen/-verplaatsingen een vergunning ingevolge de Ontgrondingenwet worden aangevraagd.

Tenslotte zullen nog diverse vergunningen benodigd zijn voor (tijdelijke) activiteiten en constructies. Deze vergunningen volgen doorgaans uit gemeentelijke en/of provinciale verordeningen.

Voor de volledigheid wordt nog opgemerkt dat vóór het in bedrijf nemen van de pomp-/elektriciteitscentrale een emissievergunning voor de emissie van CO_2 en NO_x moet worden aangevraagd.

9.2 Milieueffectrapportage (m.e.r.)

Hoogstwaarschijnlijk moet de vergunningprocedure ook een MER omvatten. De m.e.r.-(beoordelingsplicht) kan liggen bij meerdere activiteiten (exploratie en winning van het zout, de opslag van de gecomprimeerde lucht, de elektriciteitscentrale en de aansluitingen op het gasnet en het elektriciteitsnet). Bepalend voor het vaststellen van de m.e.r.-(beoordelings) plicht is in het concrete geval afhankelijk van de locatie(s), tracé(s), de capaciteit van installaties en de leidingafstanden.

Overigens wordt opgemerkt dat er geen absolute ondergrenzen zijn waarbij het opstellen van een MER zeker niet aan de orde is. De drempelwaarden voor m.e.r.-beoordeling (zie Bijlage A) moeten op grond van een wijziging van de m.e.r.-regeling van 1 april 2011 als indicatief worden beschouwd. Dit betekent dat het bevoegd gezag hoe dan ook (ook in het geval drempelwaarden niet worden overschreden) moet beoordelen of er sprake is van belangrijke gevolgen die nopen tot het opstellen van een MER.

9.3 Rijkscoördinatieregeling (RCR)

De rijksoverheid kan bij projecten van nationaal belang de vergunningen en andere besluiten coördineren. Energieprojecten, waartoe het CAES project ook gerekend kan worden, worden gecoördineerd door de minister van Economische Zaken, Landbouw en Innovatie (EL&I).

In de Rijkscoördinatieregeling (RCR) worden de verschillende besluiten (vergunningen en ontheffingen) die voor een project nodig zijn tegelijkertijd en in onderling overleg genomen. Het gaat naast vergunningen en ontheffingen vaak ook om een Rijksinpassingsplan (RIP). Dit is een ruimtelijk besluit van het Rijk, vergelijkbaar met een bestemmingsplan.

Alle besluiten voor een project worden tegelijkertijd in ontwerp ter inzage gelegd. Op dat moment kan iedereen daarop een inspraakreactie geven, ook wel 'zienswijze' genoemd. De overheden nemen daarna de definitieve besluiten ook weer tegelijkertijd, rekening houdend met de ontvangen adviezen en zienswijzen. Als een burger of organisatie het niet eens is met een of meer van de besluiten, kan hij in de meeste gevallen direct in beroep bij de Raad van State. Er is dus geen bezwaarfase.

Verantwoordelijkheden van betrokken partijen

Het Rijk kan er dus bij een project voor kiezen om zelf het ruimtelijke besluit te nemen. Veel verantwoordelijkheden blijven bij rijkscoördinatie echter ongewijzigd:

- de initiatiefnemer blijft verantwoordelijk voor een goede projectvoorbereiding en het aanvragen van alle benodigde vergunningen en ontheffingen

- de vergunningen en ontheffingen, ook wel 'uitvoeringsbesluiten' genoemd, blijven de verantwoordelijkheid van dezelfde overheden als wanneer het project niet door het Rijk gecoördineerd zou worden. De provincies besluiten bijvoorbeeld zélf over de omgevingsvergunning.

De coördinerende minister bepaalt echter, in overleg met de betrokken overheden, wanneer alle ontwerp-besluiten en definitieve besluiten genomen worden. Ook verzorgt deze minister de terinzagelegging. Alle logistieke taken van de coördinerende minister worden door Bureau Energieprojecten uitgevoerd: coördinatie van de betrokken partijen, kennisgeving en terinzagelegging, ontvangen van inspraak, etcetera.

Als uitvoeringsbesluiten op problemen stuiten, heeft de minister van EL&I de mogelijkheid om, in overleg met de minister van VROM, deze besluiten zelf te nemen (doorzettingsmacht). Hier wordt in de praktijk terughoudend mee omgegaan.

Procedure
In Bijlage B zijn de te volgen procedurestappen volgens de RCR omschreven. In grote lijnen kan qua doorlooptijd gerekend worden op:
- opstellen MER en vergunningaanvragen, inclusief alle onderliggende studies => 12-18 maanden
- besluitvorming (procedure tot vergunningverlening) => 7-10 maanden
- eventueel beroep => 6-10 maanden.

9.4 Situatie Heiligerlee (Provincie Groningen)

Uit de technisch-economische evaluatie is gebleken dat het bestaande caverneveld van Heiligerlee het meest geschikt is als opslaglocatie. Daar de directe omgeving fysiek en planologisch geen ruimte biedt voor het situeren van de bijbehorende elektriciteitscentrale moet daarvoor worden uitgeweken naar een andere locatie, op niet te grote afstand en met een bestemming of omgeving die vestiging van een industriële installatie mogelijk maakt.

De locatie die hiervoor het meest geschikt is Zuidbroek (locatie Hondenlaan, in de nabijheid van het in aanbouw zijnde stikstofmengstation van Gasunie; zie verder). In het vervolg wordt verder ingezoomd op deze locaties om het af te leggen vergunningtraject te concretiseren en de haalbaarheid van het CAES project nader te toetsen.

Vergunningprocedures

Door gebruik te maken van de bestaande zoutwinlocatie Heiligerlee behoeft in het kader van de Mijnbouwwet alleen een opslagvergunning te worden aangevraagd en goedkeuring van het opslagplan te worden verkregen. Een Wabo-vergunning moet worden aangevraagd voor diverse onderdelen van het project, met name de opslaglocatie (bovengronds deel), de elektriciteitscentrale, de tussenliggende persluchtleiding en de aansluitingen op het gas- en het elektriciteitsnet. Voor de overige zekere of mogelijk noodzakelijke vergunningen wordt verwezen naar Bijlage A.

Rijkscoördinatieregeling

Op het project is de Rijkscoördinatieregeling van toepassing vanwege de opslag in de ondergrond van stoffen (Mijnbouwwet art 141a, aanhef en onder b). Aangezien op de opslaglocatie en de locatie voor de elektriciteitscentrale alsmede de tracés nog niet de vereiste bestemmingen rusten moet ook een Rijksinpassingsplan worden opgesteld.

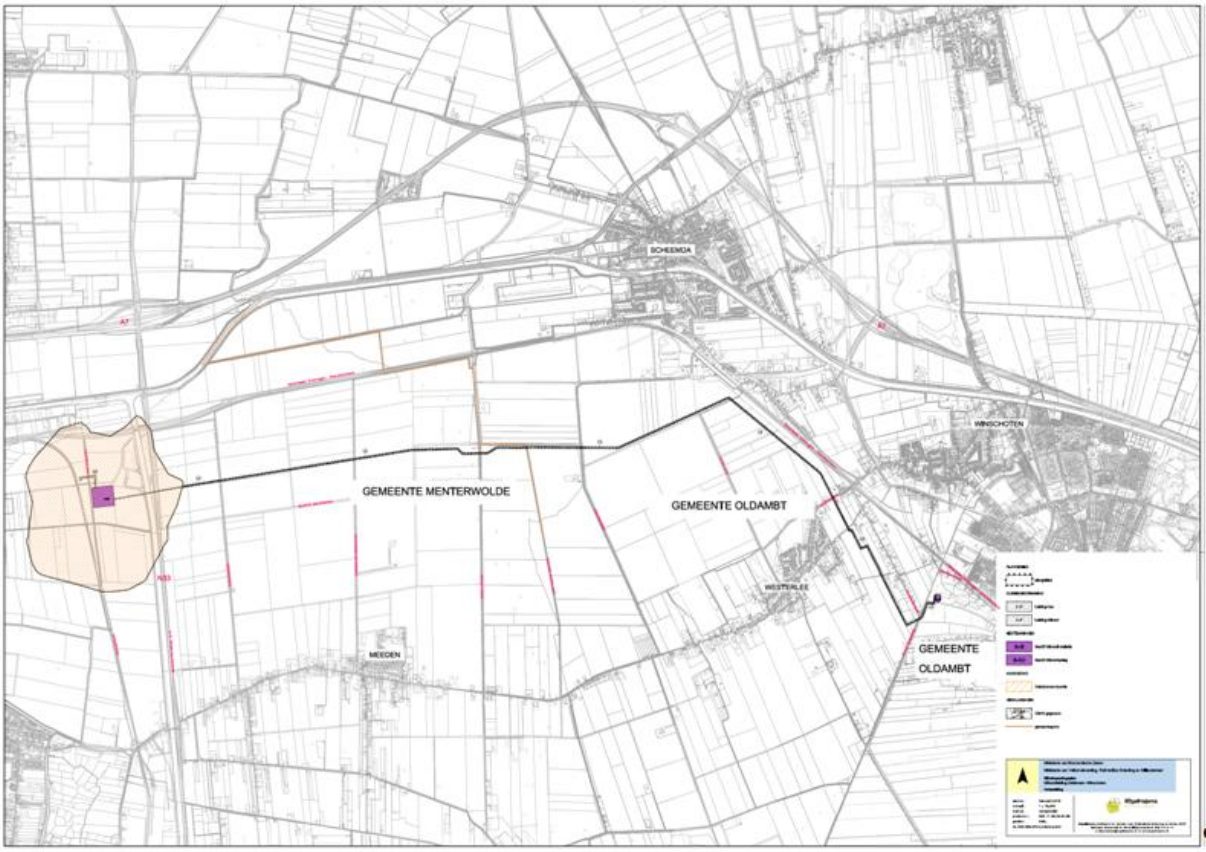
M.e.r.-plicht

Aangezien voor de elektriciteitscentrale wordt uitgegaan van een vermogen van 300 MW moet een project-MER worden opgesteld. Vanaf een vermogen van 200 MW is een plan-m.e.r. plicht van toepassing en een project-m.e.r. beoordelingsplicht. De m.e.r.-regeling komt er op neer dat het plan-MER en het project-MER wordt gecombineerd en dat het gehele opslagproject (ondergrondse deel en bovengrondse installaties en leidingen) tot de scope behoort.

Ruimtelijke inpassing (project "Stikstofbuffer" als voorbeeld)

Gegeven de voorkeur voor een opslag bij Heiligerlee en een elektriciteitscentrale bij Zuidbroek (locatie Hondenlaan) ligt de vergelijking met het stikstofbufferproject van Gasunie zeer voor de hand. Dit project zal volgens de planning in de loop van 2013 operationeel zijn. De stikstofopslag vindt immers plaats in Heiligerlee (gemeente Oldambt) terwijl de stikstofinstallatie in Zuidbroek (gemeente Menterwolde) is gesitueerd.

Voor het project is de Rijkscoördinatieregeling toegepast. De ruimtelijke inpassing van de stikstofbuffer volgens het Rijksinpassingsplan is bij wijze van voorbeeld opgenomen in onderstaande figuur @.@.



Figuur 2.@ Inpassing Stikstofbuffer (rechts op de kaart: opslag, links: stikstofinstallatie met 50 dB(A) geluidscontour en tussenliggend stikstofleidingtracé). Het tracé heeft een "dubbele bestemming"

Mede op basis van het Rijksinpassingsplan voor de stikstofbuffer kan het volgende worden geconcludeerd over de ruimtelijke inpassing van de opslag bij Heiligerlee, de bijbehorende elektriciteitscentrale bij Zuidbroek en de aansluitende leidingen:

- enkele zoutcavernes bij Heiligerlee hebben gunstige eigenschappen voor de opslag onder druk van stoffen en kunnen daartoe worden bestemd
- de locatie Hondenlaan bij Zuidbroek kent geen planologische bezwaren en past in de visie van vigerende ruimtelijke plannen. De gemeente Menterwolde en de gemeente Veendam werken samen aan de ontwikkeling van dit gebied ("Oostboog" deelgebied "Veenwolde") tot een bedrijfslocatie die geschikt is voor zware bedrijvigheid
- in de onmiddellijke nabijheid van de locatie ("Veenwolde") liggen gasleiding waardoor de aansluiting hierop over zeer korte afstand kan plaatsvinden

- aannemende dat de persluchtleiding samen kan vallen met de stikstofleiding geldt voor het tracé dat deze zo kort mogelijk kan worden gehouden (bijna 10km) en zoveel mogelijk wordt gebundeld met andere leidingen en dat daarbij gevoelige bestemmingen worden ontzien
- op basis van gesprekken met TenneT moet de netaansluiting over relatief grote afstand worden gerealiseerd. Vergunningaanvragen zullen daarom tijd kosten en er bestaat kans op extra procedureslagen

Slaagkans, doorlooptijd

De slaagkans voor het verkrijgen van de benodigde vergunningen voor CAES kan als groot (>90%) worden ingeschat om de volgende redenen:

- in hun algemeenheid kunnen energieprojecten in de provincie Groningen op een groot bestuurlijk en maatschappelijk draagvlak rekenen aangezien zij bijdragen aan versterking van de sleutelpositie op het gebied van energievoorziening (Energy Valley)
- activiteiten rond zoutwinning en aardgasvoorziening kennen in de provincie een lange historie in het kader waarvan AkzoNobel en Gasunie een duurzame relatie hebben opgebouwd met de Groningse samenleving
- voor het CAES project ligt een locatiekeuze in de rede die aansluit op het project "stikstofbuffer". Het Rijksinpassingsplan voor dat project toont aan dat de ruimtelijke inpassing niet op grote problemen hoeft te stuiten. Tegen de uitvoeringsbesluiten is geen oppositie gevoerd vanuit de besturen en de bevolking van de gemeenten Oldambt en Menterwolde
- de locatie(s) stuit(en) niet op bezwaren van enige betekenis vanuit het oogpunt van natuur.

Doorlooptijd

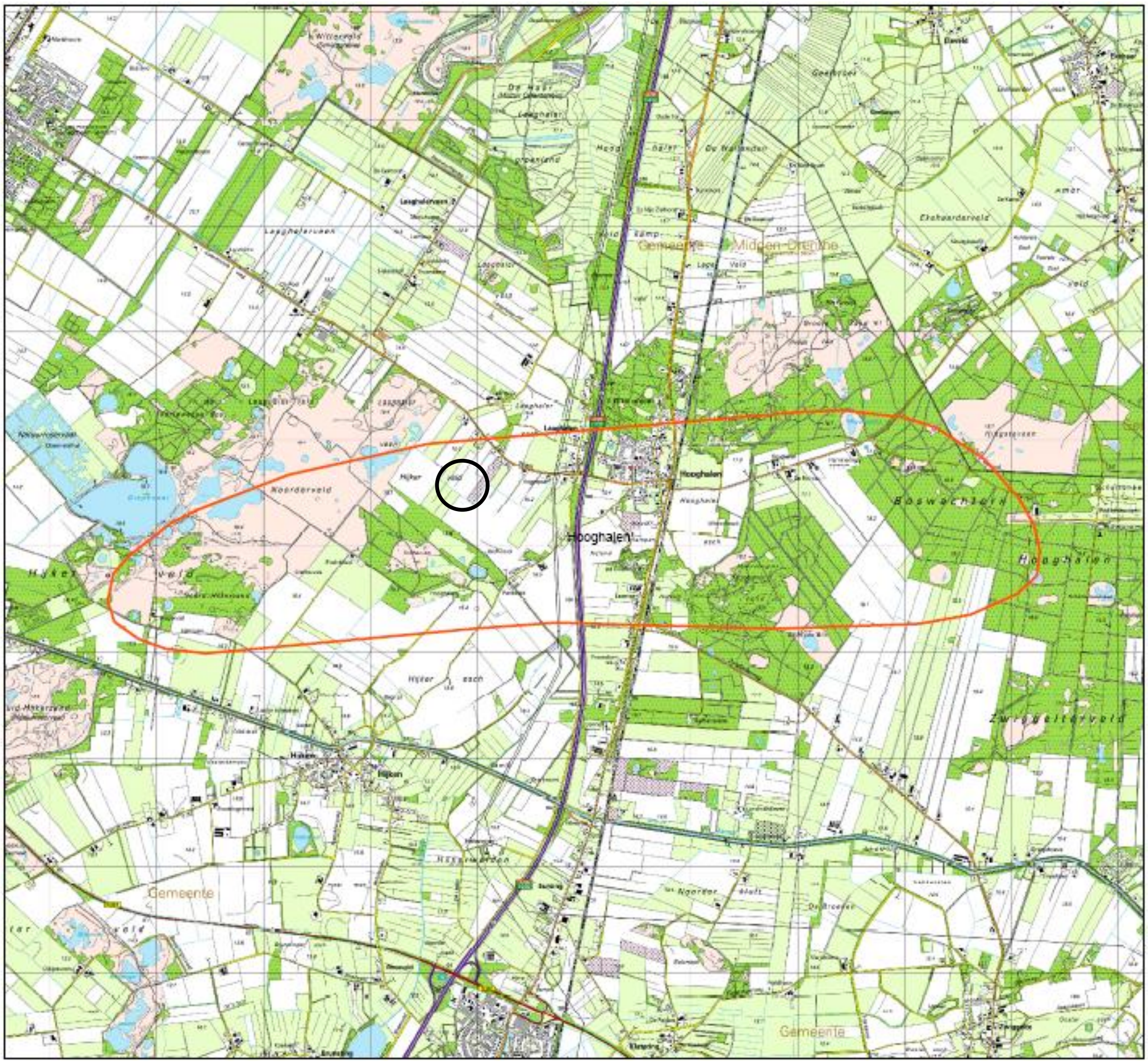
In het navolgende overzicht wordt de te verwachten doorlooptijd aangegeven op basis van wettelijke proceduretijden, gerealiseerde doorlooptijden van vergelijkbare projecten en ervaringen van KEMA op basis van een scenario waarin gemeente en provincie volledig meewerken aan de vergunningverlening.

Tabel @.@ Verwachte doorlooptijd voor vergunningen (exclusief eventueel beroep)

Mijlpaal	**Doorlooptijd (in mnd)**	
	Fase	**Cumulatief**
Start project	0	0
Opstellen en indienen MER+vergunningaanvragen	14	14
Opstellen en terinzagelegging Ontwerp-Rijksinpassingsplan / Vergunningen	5	19
Definitief Plan en Vergunningen	6	25

9.5 Situatie Hooghalen (Provincie Drenthe)

Zoals eerder reeds is uiteengezet is er in de provincie Drenthe een mogelijk geschikte locatie vanwege de aanwezigheid in de ondergrond van een omvangrijk zoutvoorkomen: de omgeving van Hooghalen (gemeente Midden Drenthe). De contour van de zoutkoepel is weergegeven in figuur 9-1.



Figuur 9.1 Zoutkoepel Hooghalen met mogelijke locatie zoutwinning en CAES energieopslag

Uit overleg met de provincie is een locatie ten westen van Hooghalen, globaal tussen De Streek (de weg richting Smilde) en het Hijkerveld als een mogelijke optie naar voren gekomen (zie figuur @.@). Het betreft een landelijk gebied, waar weinig mensen wonen. Er zijn nog geen plannen voor zoutexploratie en –winning of andere ontwikkelingen in het gebied. Voor de onderhavige studie betekent dit dat de locatie vanuit een "greenfield" situatie zou moeten worden ontwikkeld inclusief alle benodigde bestemmingen en vergunningen. Vooralsnog wordt voor de verdere beschouwing uitgegaan van een geïntegreerd complex voor zoutwinning, pekelverwerking en energieopslag inclusief de pompcentrale en aansluitingen voor gas en elektriciteit.

Overigens wordt opgemerkt dat de geschiktheid van het zout ter plaatse nog niet vast staat. Exploratieboringen zullen dit moeten vaststellen.

Vergunningprocedures
Gestart moet worden met het aanvragen van een opsporingsvergunning (ook: exploratievergunning) in het kader van de Mijnbouwwet. Bij gebleken geschiktheid van het zout kunnen vervolgens de winningsvergunning en de opslagvergunning worden aangevraagd. Een Wabo-vergunning moet worden aangevraagd voor diverse onderdelen van het project, met name de winnings- annex opslaglocatie (bovengrondse installaties) en de elektriciteitscentrale. Voor de overige zekere of mogelijk noodzakelijke vergunningen wordt verwezen naar Bijlage A.

Rijkscoördinatieregeling
Op het project is de Rijkscoördinatieregeling van toepassing vanwege de opslag in de ondergrond van stoffen (Mijnbouwwet art 141a, aanhef en onder b). Aangezien op de locatie en de aansluitende tracés nog niet de vereiste bestemmingen rusten moet ook een Rijksinpassingsplan worden opgesteld.

M.e.r.-plicht
Voor wat betreft de zoutwinning en de energieopslag is er geen m.e.r.(beoordelings)plicht omdat de win-/opslaglocatie niet in gevoelig gebied is gelegen (Besluit m.e.r. cat. D.29.1).

Voor de CAES pomp-elektriciteitscentrale moet, uitgaande van een vermogen van 300 MW een project-MER worden opgesteld (C.22.1). Vanaf een vermogen van 200 MW is een plan-m.e.r. plicht van toepassing en een project-m.e.r. beoordelingsplicht(D.22.1).

De m.e.r.-regeling komt er op neer dat het plan-MER en het project-MER wordt gecombineerd en dat het gehele project (ondergrondse deel en bovengrondse installaties en leidingen) tot de scope behoort. Hoewel er strikt genomen geen m.e.r.-(beoordelings)plicht bestaat voor de ondergrondse activiteiten kan deze moeilijk los worden gezien van het CAES-project. Er zou daarom, mede vanuit het oogpunt van informatievoorziening en het verkrijgen van publiek draagvlak, voor gekozen kunnen worden om het MER op vrijwillige ook te betrekken op de zoutwinning.

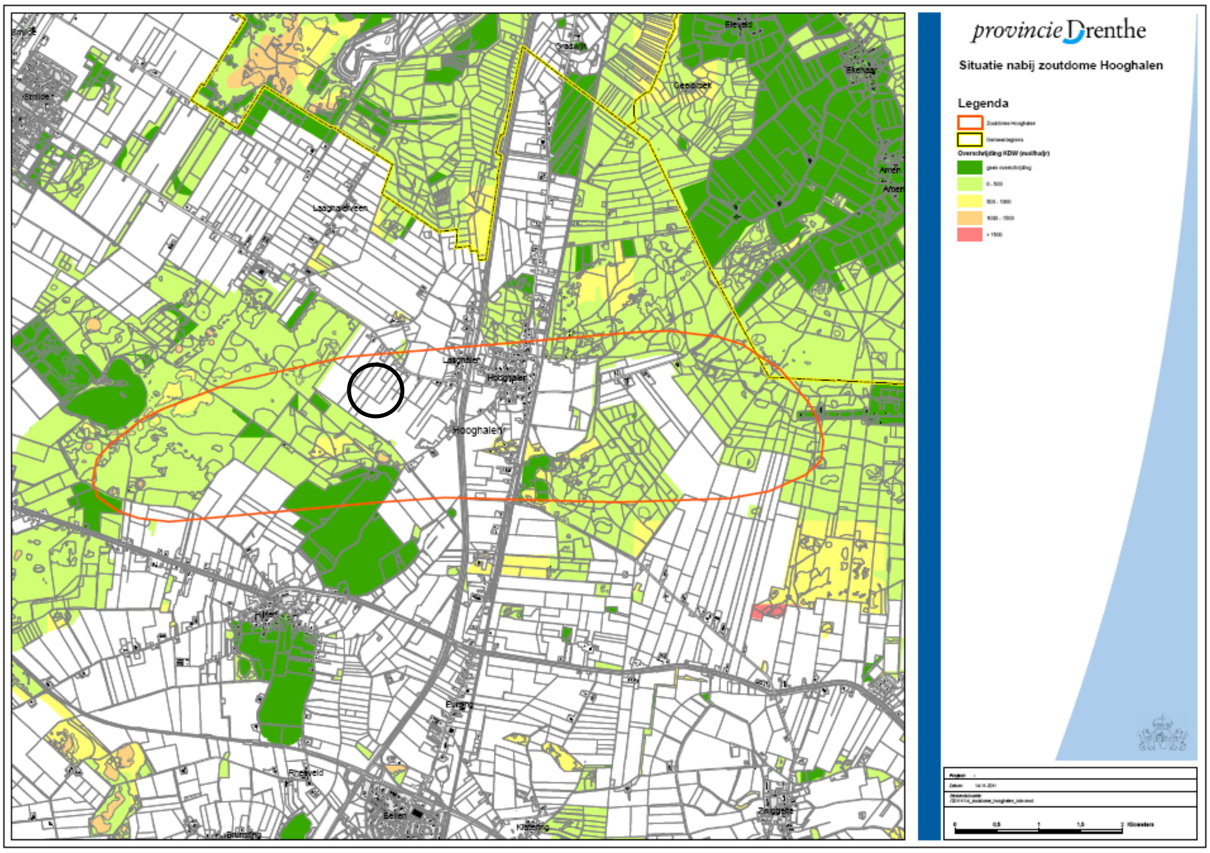
Ruimtelijke inpassing

De locatie heeft thans een agrarische bestemming en moet dus in het kader van het CAES project geheel worden herbestemd op basis van een Rijksinpassingsplan. In fysieke zin lijkt voldoende ruimte aanwezig (afhankelijk van zoneringsafstanden 40-70ha) maar rekening moet worden gehouden met begrenzingen en beperkingen vanuit gevoelige bestemmingen met name:

- woonbebouwing De Streek (ten noordoosten)
- Laaghaler Veen (ten noordwesten)
- grafheuvels (ten zuiden).

De twee laatstgenoemde gebieden behoren tot de Ecologische Hoofdstructuur (EHS) en zijn aangewezen als stiltegebied. In de EHS geldt het 'nee, tenzij' beschermingsregime en mogen de wezenlijke waarden en kenmerken van een gebied niet *significant* worden aangetast, tenzij er geen reële alternatieven zijn én er sprake is van redenen van groot open-baar belang. De effecten van het CAES complex kunnen in het bestek van deze studie niet worden beoordeeld, maar duidelijk lijkt wel dat de aspecten stikstofdepositie (als gevolg van de NO_x emissie van de centrale) en geluid (geluidzonering noodzakelijk) issues kunnen zijn voor de ruimtelijke inpassing en de vergunningverlening.

Ter illustratie is in onderstaande figuur 9-2 de situatie weergegeven met betrekking het aspect stikstofdepositie. Uit de figuur blijkt dat in grote delen van het nabijgelegen EHS-gebied de kritische depositiewaarde (KDW) wordt overschreden.



Figuur 9-2 Mogelijke locatie zoutwinning en CAES energieopslag met omliggende EHS gebieden en situatie stikstofdepositie (kritische depositiewaarde wordt overschreden in alle gebieden uitgezonderd de donkergroene)

Slaagkans, doorlooptijd

Er liggen kansen voor het realiseren van CAES in de omgeving Hooghalen inclusief het verkrijgen van de benodigde vergunningen maar er is tevens sprake van enkele omstandigheden die de doorlooptijd en de slaagkans nadelig beïnvloeden, namelijk:

- de geschiktheid van het zout staat nog niet vast
- de "greenfield" situatie impliceert dat er forse ingrepen in de omgeving moeten worden gepleegd, waarvoor alle bestemmingen en vergunningen nog moeten worden geregeld
- de provincie Drenthe wordt in vergelijking tot bijvoorbeeld de provincie Groningen minder geassocieerd met energiegerelateerde bedrijvigheid (Energy Valley) en meer met landelijke rust en kwaliteit. Activiteiten rond zoutwinning en energievoorziening zijn nieuw voor de Drentse bevolking
- de locatie Streek/Hijkerveld kent mogelijk bezwaren vanuit het oogpunt van natuur (nabijheid EHS, aspecten stikstof en geluid).

N.B.: In tegenstelling wat eerder werd aangenomen is er oppervlaktewater beschikbaar uit het Oranjekanaal/Drentse vaart voor koeling of uitloging van zout met een omvang van 10.000m3 /

24uur (ruim 400 m3/uur), dat genoeg is voor de benodigde uitloogsnelheid van 250 m3 pekel per uur om binnen 3 jaar een caverne van 600000 m3 te krijgen.

Doorlooptijd

De doorlooptijd is aanzienlijk omdat alle vergunningen in het kader van de Mijnbouwwet eerst moeten worden aangevraagd, te beginnen met de opsporingsvergunning. De aanvragen voor de winning en opslag kunnen pas gedaan worden nadat de resultaten van de exploratie bekend zijn. Voorts valt vanwege eerder genoemde factoren te verwachten dat:

- de benodigde tijd voor het uitvoeren van het MER, de onderliggende onderzoeken (met name natuur), het Rijksinpassingsplan en het opstellen van de vergunningaanvragen aanzienlijk zal zijn
- in de ontwerpfase vanuit de omgeving en mogelijk milieugroeperingen de nodige bezwaren zullen worden ingediend, met navenante gevolgen voor de doorlooptijd in de fase tot de definitieve vergunning(en).

In het navolgende overzicht wordt de te verwachten doorlooptijd aangegeven op basis van wettelijke proceduretijden, gerealiseerde doorlooptijden van vergelijkbare projecten en ervaringen van KEMA op basis van een scenario waarin gemeente en provincie volledig meewerken aan de vergunningverlening.

Tabel 9-1: Verwachte doorlooptijd voor vergunningen (exclusief beroep)

Mijlpaal	**Doorlooptijd (in mnd)**	
	Fase	**Cumulatief**
Start project	0	0
Opstellen aanvraag en verlening Opsporingsvergunning	10	10
Opstellen MER en overige Vergunningaanvragen	20	30
Opstellen en terinzagelegging Ontwerp-Rijksinpassingsplan / Vergunningen	5	35
Definitief Plan en Vergunningen	5	40

10 CONSIDERATIONS ON ADIABATIC CAES (ACAES)

The Adiabatic CAES (ACAES) is at the moment the most interesting energy storage concepts although it has still to overcome several technical challenges. This CAES concept is in fact gaining attention since it doesn't use fossil fuel, doesn't produce emission locally and has a relatively higher efficiency if compared to typical CAES. On the other hand the special characteristics of this concept require a new design of the equipment that cannot be realized with simple adaptations of existing commercial equipment.

In this chapter some relevant considerations are discussed to compare advantages and disadvantages of the ACAES with respect to the typical CAES concept.

10.1 R&D on the ACAES concept

The demonstration of the feasibility of the ACAES is the subject of the ADELE project started in January 2010 and founded by the German Federal Ministry of Economics and Technology, involving several partners including General Electrics, RWE Power and DLR (German Aerospace Center). The aim of this project is to develop the ACAES technology up to bidding maturity for the components of a first demonstration plant.

In parallel to the ADELE R&D project, the industrial partners are pushing ahead with the development of the ADELE demonstration plant. As an important milestone, the favored site for this first-of-its-kind plant has been selected in November 2010: the salt formation at Stassfurt in Saxony-Anhalt, Central Germany [Bieber 2011].

R&D activities were been already conducted in the past with the Advanced Adiabatic CAES (AA-CAES) project founded by the European Union and started in 2003[4]. The aim of this project was to perform a first feasibility assessment of this technology and to produce a conceptual design of an ACAES plant. Main partners involved were E.On Energie A.G.,
Man Turbomaschinen AG, Alstom Power Ltd and DLR.

10.2 Adiabatic CAES concept

In the ACAES the compressor is not intercooled therefore the air during compression can reach high temperatures, in the order of 620°C for a final pressure of 100 bar [Zunft 2006].

In charging mode operation the heat is extracted from the air and stored in a special Thermal Energy Storage (TES) facility. In discharging (production) mode the pressurized air is extracted from the reservoir and warmed up to approx. 600 °C using the stored heat. The combination of

[4] Info at: http://www.ist-world.org

high temperature and pressure makes possible to expand the air in a turbo-expander to produce electricity without the addition of fuel (natural gas).

This concept is called adiabatic because looking at the overall system the process happens with (ideally) no heat exchange with the surroundings, in fact the heat produced during compression is not dissipated to the environment with intercoolers but is conserved in the thermal storage for a later re-utilization during operation mode. In this concept the cooling systems for the intercoolers is almost eliminated but instead a big heat storage facility has to be included.
A simple scheme of the ACAES configuration is represented in Figure 10.1 while Figure 10.2 show an artistic rendering of a future ACAES plant.

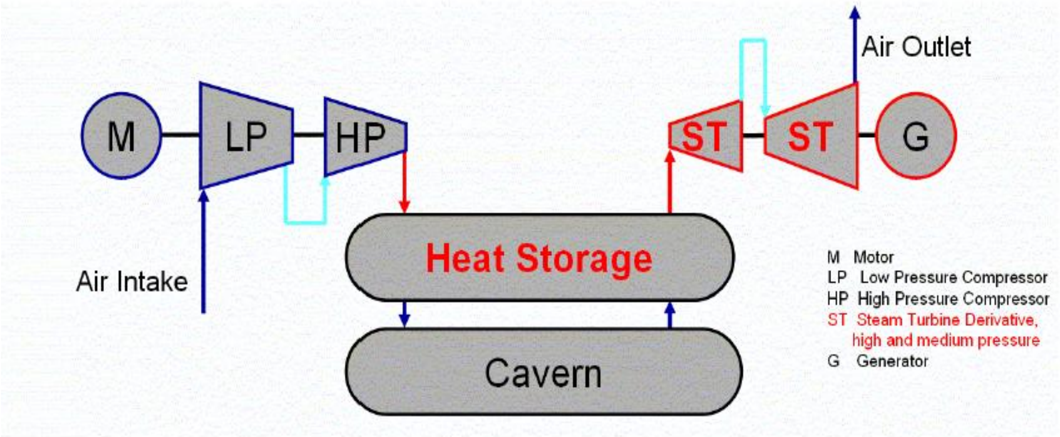


Figure 10.1 Principle of advanced adiabatic CAES [Bullough 2004]

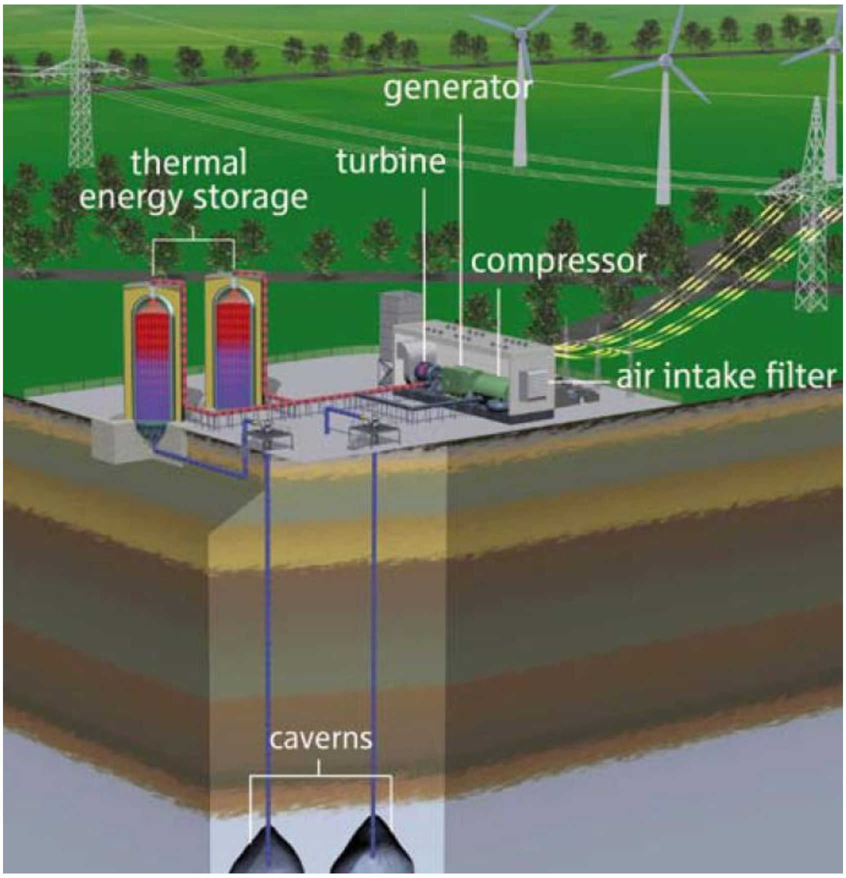


Figure 10.2 Artist rendering of ACAES plant [RWE 2010]

10.2.1 **Higher round-trip efficiency**

The resulting round-trip efficiency of this system is estimated to be around 70% [Bieber 2011]. This efficiency is higher than 45-60% efficiency achievable in the typical CAES concepts. The improvement is due to the fact that in the ACAES most of the heat released during compression is re-used in the system instead of being dissipated to the environment.
This concept doesn't need therefore to use fossil fuel to run the turbo-expander because the heat to warm up the compressed air is provided by the system itself.
The estimated efficiency is, however, the results of a preliminary process design and for the real plant it may turn out to be lower, especially if the thermal energy storage is not performing as expected.

10.2.2 Avoided natural gas use and emissions

The relatively higher efficiency of the ACAES reflects on lower net CO_2 and pollutant emissions per KWh, therefore the environmental impact in terms of emission is reduced with respect to typical CAES plants.
Because the fuel consumption is eliminated the ACAES is a "pure" energy storage system; also emission of CO_2 and pollutants are locally eliminated or strongly reduced. Implications in plant design and realization related to natural gas grid connection and emission are therefore avoided. However it is likely that some limited fuel consumption is still needed for start-up of the expander, especially if fast startup is a main requirement for the plant, and also to keep warm the turbine rotor and casing during stand-by period in order to reduce thermal cyclic stress.

10.2.3 Thermal Energy Storage (TES)

Since compression and expansion takes place in different moments of the day the ACAES plant has to include a Thermal Energy Storage (TES). The heat storage is a central element in the ACAES plant and its performance is of decisive importance for the level of the efficiency of the overall process. A proper TES for this application must fulfill the following requirements:

- High storage capacity,
- High storage and discharge air flow rates,
- Rather constant exit temperature,
- Operation under high pressure,
- Low temperature losses,
- Low specific investment cost,
- Long lifetime.

Large amounts of thermal energy have to be stored in the TES at a temperature level above 600°C and high operating pressure (i.e. 100 bar). For a 300 MW_e plant the thermal storage needs to have a capacity of approximately 2400 MWh_{th} at high extraction rates and high uniformity of outlet temperature is required; at the same time charging and discharging losses of temperature and pressure need to be kept low to achieve high process efficiency levels [Zunft 2006].

A review of the possible TES technologies has been one of the subjects in the ADELE project, revealing major differences in their ability to meet process demands, in their investments costs and in their technology maturity. TES solutions based on solid storage media (e.g. ceramic bricks, natural stones) are particularly promising, as they allow a direct contact between the air stream and the storage inventory [Bieber 2011]. A wide range of storage media and geometries is being currently explored in the ADELE project to find the optimal economical and technical solution. Table 10.1 shows a shortlist of possible concepts using solid storage media.

Table 10.1 Shortlist of possible TES concepts [Zunft 2006]

	Solid TES				
Concept	Rock bed	Cowper-Deriva-tive	Concrete Walls	Cast Iron Slabs	‚Hybrid' PCM
	direct	direct	Direct	direct	direct
Inventory Material	Natural stone	Ceramics	Concrete	Cast Iron	Ceramics or Salt

Also the AA-CAES project came previously to similar conclusion asserting that solid storage media (direct contact) is the most favorable solution. A conceptual optimized design indicated that a modular setup of cylindrical structures made of pre-stressed concrete is advantageous. The storage volume was estimated to be around 10.000 m^3 for a 300 MW_e plant [Zunft 2006]. An example of direct heat storage with dimensions is given in Figure 10.3.

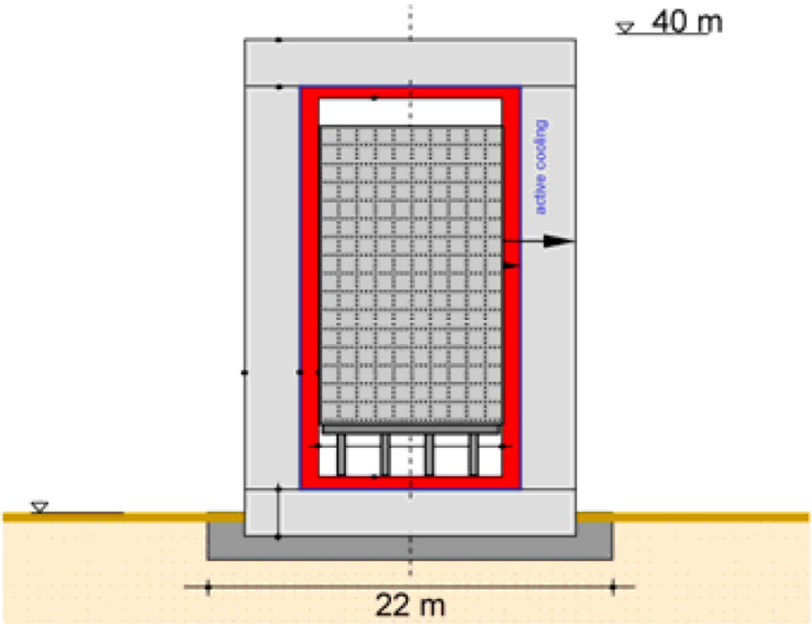


Figure 10.3 Example of direct heat storage and its dimension [Zunft 2006]

Although thermal storage allows a higher round-trip efficiency of the plant, the costs associated with this component are relevant and increase significantly the investment cost of the ACAES installation. Another disadvantage associated with the TES is the visual impact of the plant having this component a relatively large volume.

The main issue however remains the fact that at the moment there are no TES system suitable for this type of application and the development of TES fulfilling the several requirements will probably take several years of R&D.

10.2.4 **Compressor design**

In a typical CAES application, like the Huntorf plant [Crotogino 2001] and the McIntosh plant [Daly 2001], industrial intercooled compressor are used with minor adaptation to the turbo-machinery design; this is not the case for ACAES plants.
In an ACAES application the compressor is not intercooled resulting in high operating temperature and pressures. The combination of high pressure and temperature at the compressor outlet is unusual in industrial scale applications and represents a technical challenge for which no commercial solutions are available as yet [Del Turco 2009].

A new high pressure and high temperature design is required, based on industrial compressors and allied to high temperature technologies of steam turbine and gas turbines.
Because of the high discharging temperature, material characteristics, thermal expansion phenomena and sealing concepts have to be studied in detail. The pressure containing equipment is subjected to high loads. The thermal expansion caused by operation at high temperatures induces changes in clearances and has to be analyzed thermo-mechanically to predict and understand the part-load operability of the compressor train [Bieber 2011].

The study presented in [Zunft 2006] stated that the most promising layout includes a low pressure axial intercooled compressor followed by single shaft centrifugal compressors designed for high temperatures (Figure 10.4). Although the adiabatic concept approach theoretically does not include intercooling, a realistic concept needs a small amount of intercooling to decouple charging pressure from the end temperature [Zunft 2006].

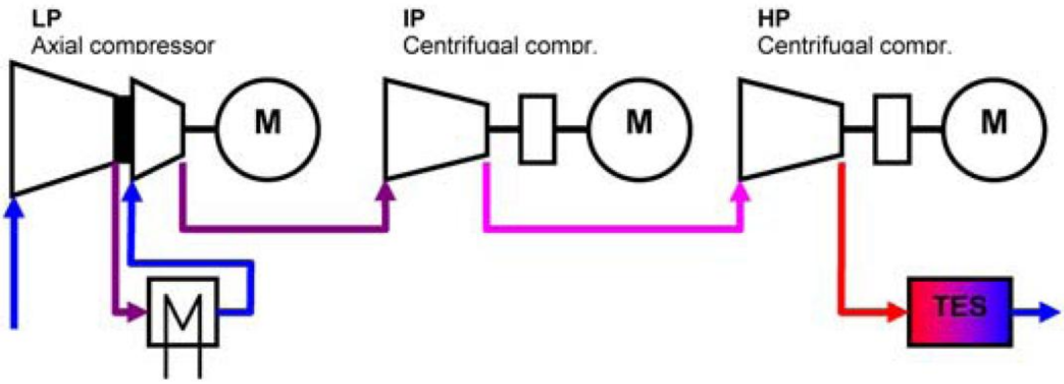


Figure 10.4 Basic compressor train layout for ACAES [Zunft 2006]

Turbo-machinery development work is founded in parallel to the ADELE project by RWE and GE Oil & Gas. The expected outcome will be a preliminary aerodynamic and mechanical compressor design [Bieber 2011].

10.2.5 Turbo-expander design

Similarly to the compressor, also the turbo-expander requires a special design for ACAES applications. The operating pressures to be expected, for example, far exceed the inlet pressures of today‘s gas turbines. Moreover, the turbine must cope with the considerable fluctuations in pressures and throughput amounts when the storage facility is discharged, for which an optimized controlling system has to be developed.
The air turbine is also one of the subjects in the ADELE project: General Electric‘s task is to adapt existing turbine technology for use in ACAES applications [RWE 2010].

10.2.6 Comparison CAES and ACAES

The consideration discussed in previous paragraphs of Chapter 5 are summarized Table 10.1.

Table 10.1 Comparison between CAES and ACAES

CAES	ACAES
More innovative CAES plant concept could reach a round trip efficiency around 60%	Round trip efficiency estimated around 70%
Use of natural gas	Avoided (or little) natural gas consumption
Local emission of CO_2 and pollutants	No (or little) local emission of CO_2 and pollutants
Compressor commercially available	New design of compressor required
Turbo-expander (gas turbine) commercially available	New turbo-expander design required
Plant needs a cooling system	No cooling system
No thermal storage	Thermal energy storage needed (still under R&D)

10.3 ACAES feasibility

The growing interest in ACAES solution is motivated by the need of more efficient and "clean" solution with respect to the typical CAES; ACAES can really offers these advantages however it must be proven in a demonstration facility that up to date doesn't exist. Moreover, the realization of the main equipment, especially the compressor and the thermal energy storage, require some years of research to overcome the technical bottlenecks aforementioned in this chapter. It is not clear how much R&D effort will be needed to find suitable solutions and implement them in a demonstration facility.

Currently is not possible to build an ACAES plant, due to technical constrains; perhaps in the medium terms technical issues will find a solution and will be possible to realize a first-of-its-kind ACAES plant.

Before any investment decision, due to the high risk associated, a demonstrative facility must be awaited.

11 CONCLUSIONS AND DEVELOPMENT PLAN

11.1 Technology selection

Technically, it is feasible to design and construct the surface parts of a Compressed Air Energy Storage plant. It has been demonstrated in practice, components are available and the overall round trip efficiency can increase compared to the existing plants.

The table shows the evaluation of design concepts.

Table ranking criteria for each concept

CAES Concept	Simplicity	Flexibility	Maturity	Efficiency	Sustainability
Conventional	++	++	+	--	-
Recuperated	+	++	+	+/-	-
Recuperated Optimized	+	++	+	+	-
Adiabatic	-	-	--	++	+
Combined cycle	--	--	+/-	++	-
Steam injection	-	+/-	+/-	+	-
Humid air	+/-	+/-	+/-	+	-

Legend: ++ Very high, + High, +/- Medium, - Low, -- Very Low

11.1.1 Standard Compressed Air Energy Storage

The optimized recuperated CAES concept has been selected from seven alternative design concepts as the most feasible plant design. The design basis reflects the experiences acquired in McIntosh and Huntorf, yet it offers clearly improved round trip efficiency. Most components of the plant are well known and available in the market. It is a simple concept, it has a relatively short start time and steep ramp rate. It can be realized on relatively short term and without additional research and development work.

The least positive aspect for this technology is the overall sustainability: the heat generated at air compression cannot be stored and is emitted into the environment, unless an application can be found in e.g. district heating or industrial heating. Such additional concepts have not been studied here.

Improvements

The high pressure required by the depth of the caverns imposes some negative consequences on the design:

- The roundtrip efficiency decreases with higher pressure: more heat is wasted during compression
- All equipment needs to be designed and engineered for higher pressure values, which increases the investment cost.

From this point of view, reducing the operating pressures in the caverns has to be researched. Either by looking for caverns at lower depth or looking to apply lower pressures in deep caverns (which results in soil subsidence, but is applied in e.g. Huntorf).

11.1.2 Adiabatic Compressed Air Energy Storage

For several reasons, the Adiabatic Compressed Air Energy Storage is not selected for further research in this feasibility project. The major advantage of the ACAES technology obviously is in the energy efficiency by storing the compression heat for use during expansion. This could eliminate the need for additional fuels and make it an important element in a truly sustainable power chain. Another advantage is that at the moment of electricity production, which is at high energy prices, additional gas (that also will be at a high price) will not be necessary. As a side effect, it could eliminate the need of a gas connection.
Since the ACAES technology is currently in an early phase of development and demonstration, with ongoing research into the best ways to store energy under high pressure, it is simply too early to consider this design concept on an equal basis with the other concepts.
Several elements have impact on the feasibility of ACAES:

- *Relatively low flexibility in power production.*

Heat storage is more limited than pressurized air storage, due to heat losses. For sudden, temporary, short term responses, e.g.to respond to imbalance, there may be enough air in the caverns, but insufficient heat in storage. The operations are therefore limited to fixed day-night cycles

- *High investment costs*

For large scale heat storage, a very large concrete vessel needs to be constructed. Construction materials in themselves are cheap, but the overall additional investment is considerable. We estimate 250-450 €/kW will need to be added to the investment cost. Storing heat directly in a pressurized vessel is still preferred over storage in e.g. molten salts.

- *Need for new equipment*

Both the compressor and the turbo expander need to be redesigned for this purpose, and cannot be bought as standard equipment.

11.1.3 Plant location and design

Considering the most likely cavern location in Groningen, the best location for a power plant itself will be situated in an industrial area within approximately 10 km. Based on a similar case for Nitrogen storage in Heiligerlee where the pumping station is situated in Zuidbroek.

Power network connections require connections over 18-25 kilometers to 220 kV stations. This is feasible, but will require considerable permitting efforts and of course induce additional costs. Connection to the 110 kV network is not (yet) accepted by TenneT.
Connecting to the gas network is feasible, given the availability of gas transport lines in the area. Detailed connection studies will need to be made in the next phase. Gas networks can be found close to Zuidbroek.

11.2 Cavern availability

KEMA has considered the situation on both Provinces of Groningen and Drenthe. At the same time, we consider the use of existing salt caverns and the creation of tailor made new caverns in existing salt layers.

11.2.1 Groningen

It is feasible to use existing salt caverns in the Heiligerlee area for CAES. Out of five caverns selected by AkzoNobel, one is immediately suited to accommodate a CAES plant of 300 MW. Even with a storage capacity of 12 hours of power production, the daily pressure variation remains under 10 bar. Increasing the piping diameter by additional drilling of pipes is required to obtain the requested capacity and in order to reduce pressure losses.
Two more caverns have the right dimensions, but are too close to housing and would need additional measures for safety. With additional cavern mining (increase the top volume), another cavern can be made available in the same area.
The disadvantage of the caverns is their depth, leading to high working pressures in order to prevent subsidence.

Caverns in the Zuidwending area have not been proposed by AkzoNobel, because of the depth and shape of the caverns. The top of the salt dome is at less depth than Heiligerlee (200 vs. 400 m), so potentially this would be a better location for CAES caverns. In order to make the existing caverns fit for use for CAES; additional mining would have to take place. The infrastructure for brine transport can be used. Another advantage of Zuidwending is the distance to housing; it is a more rural area.

11.2.2 Drenthe

For Hooghalen, an “ideal cavern” has been considered. The size of the total salt layer near Hooghalen allows for flexibility in making one or even a number of caverns. This ideal cavern has an operating pressure close to 30 bar, so it either is situated relatively “shallow” or it is situated in an area where a deeper cavern with lower operating pressure is possible, e.g. when some soil subsistence is allowed.
The volume of the cavern is balanced with the maximum allowed pressure variation of 10 bar. For 300 MW and 6 hours of storage, this would result in approximately 0,6 Mm3. A bigger cavern however offers the advantage of smaller pressure variation, so more constant operation of the plant or an increase in capacity per day.
For the shape of the cavern it is of importance to have a 'smooth' form for which a stability analysis can be performed. The ideal shape is near cylindrical or pear like, vertically oriented, in order to minimize soil subsidence.
The ideal cavern has one large diameter pipe or multiple pipes connecting the cavern to the power plant, in order to reduce friction losses at the high required capacity.

It is important to notice that caverns made ideally for CAES are not well suited for future storage of natural gas or nitrogen, because these substances are stored at higher pressures and hence at increased depth.

In Hooghalen, a specific site was selected by Provincie Drenthe for positioning of the power plant. The first cavern would logically be situated near that site. No research was done into the geological aspects of a location. The top of the cavern is around 300 meter, so until now it is uncertain which depth and pressure can be obtained.

11.2.3 Surface impacts

Mining several millions of cubic meters from a depth of 1-2 km can have seriously impacts at the surface level, either causing subsidence (bodemdaling) or light shocks when underground layers move more rapidly. This study indicates that the risk of surface impacts is limited, certainly when general rules are observed, such as minimum distance to other caverns, minimum distance to top or sides of salt layers, maximum pressure differences per day and so on.

11.3 Costs and benefits CAES

11.3.1 Value Assessment

The CAES system has been modeled and put in a Plexos simulation of the European power market. With this simulation, three scenarios have been assessed: Business as Usual, Nuclear Moratorium, Sustainable Development, each with different cost and price development ranges.
A CAES system can basically be used for

- Power trading (or spot market), buying power cheap in the night and selling it more expensive during the day.
- Balancing markets, providing additional supply or demand to balance the power in a certain region or country

The simulations show that a positive Net Present Value can only be found in the Sustainable Development scenario, where a high percentage of stochastic renewable power is fed into the market and the need for flexible adjustment is highest.
The simulations also demonstrate that the value gained at spot markets is not sufficient in any scenario; providing reserve power is a prerequisite for a positive business case.
Revenues largely based on the reserve market are sensitive to adjustments in national regulation regarding balancing and reserve provision.

Investment and Net Present Value (M€)

	pessimist	base case	optimistic
investment	-391	-280	-168
Business as Usual	-313	-202	-90

Nuclear Moratorium	-400	-289	-177
Sustainable Development	439	550	662
Sustainable Development – after 15 yrs	128	239	351

From a purely value point of view, CAES can become feasible in a Sustainable Development scenario, even when other sources of sustainable balancing power will be developed (more hydropower use from Norway, e.g.) . It is hard to say when, and under which conditions, the Sustainable Development scenario may become reality. This will require further research. The direct financial feasibility of CAES (and ACAES) therefore is considered to be low. The same conclusion can be found in a recent article from the German ADELE project.

11.3.2 **Cost Assessment**

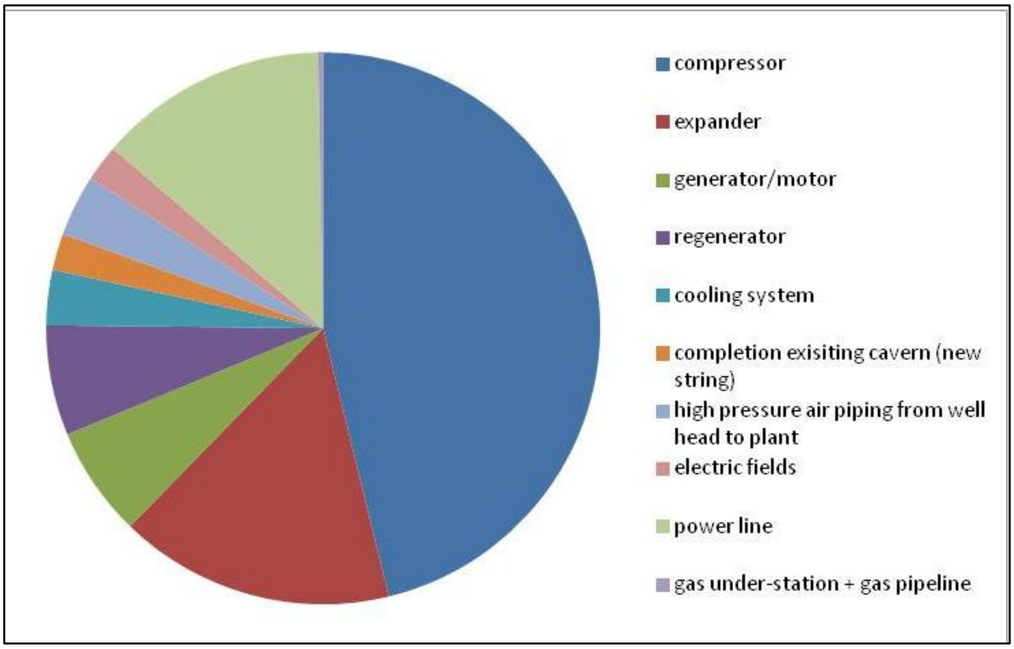
Costs of CAES plants have been assessed using three approaches:

- literature on CAES
- comparison to gas fired power plants
- bottom up estimate of CAES plant cost

It proved important to understand the definition of “specific cost” for a CAES plant, which is different for a normal gas turbine plant.

Cost of a 300 MWe CAES plant is estimated at 280 M€ plus or minus 40%. The majority of the cost is in the compressors with intercooling. The grid connection is also relatively expensive, due to the long distance to the nearest point of connection indicated by TenneT.

Cost of creating a cavern has not been included, since the base case for Groningen is based upon reuse of existing caverns.



Drenthe situation

For Drenthe, the majority of cost remains the same. The grid connection is probably in the same order of magnitude, but the gas connection may be more expensive, due to a longer distance to the gas grid. In Drenthe, when combining the cavern with the plant, investments in high pressure piping and in completion can be reduced. These are not the major investments.

Adiabatic CAES

KEMA did not make detailed estimates about the cost of A-CAES. As a first indication, the investment cost will rise considerably because of the massive (concrete/steel/stone) heat storage structure. The compressor will change considerably, (no intercooling, but high temperature compression) and also the expander has to change. The gas connection can be reduced. Our estimate is that the investment cost will rise.

11.4 Permits

Two options were considered: use an existing cavern in the Heiligerlee area (Groningen) and create a new cavern in the Hooghalen area (Drenthe). Both projects are subject to the RijksCoordinatieRegeling (consequence of the Crisis and Herstelwet), since caverns are used for storage.

11.4.1 Groningen

Only recently, a complete permitting process has been executed for the storage of Nitrogen in a Heiligerlee cavern. This has been used as a basis for our estimates. Using a cavern for CAES in the Heiligerlee area implies siting of a power plant in a nearby industrial area, such as Zuidbroek. An environmental impact assessment is required for the power plant. The industrial area is not yet suited for a power plant. A power line needs to be planned to a location at 20+ kilometers. This will certainly require additional effort.

The feasibility of obtaining all permits for use of the cavern and realization of the power plant and connections is estimated at least 90%. Obtaining all permits will at least require 2 years, excluding potential appeals.

11.4.2 Drenthe

The Hooghalen case is literally a “green field”. The province of Drenthe has tentatively indicated an area for development of the caverns and realization of a power plant (and potentially a salt refinery), west of the motorway A28. This is only a test case; it does not reflect an official standpoint whatsoever. The starting point for Drenthe in this selection is the search for a location which offers enough space, good connections, and is close to the salt dome. By combining surface and subsurface facilities, efficient designs can be made, e.g. combining waste heat reuse in brine treatment.

Since no salt caverns are present, they first have to be created by extracting brine (solution mining).

Serious permitting issues include:

- Supply of water for solution mining
- NOx deposition: this seems feasible, but may become more difficult when a power plant is combined with a salt plant
- Close distance to EHS areas
- Detailed spatial planning considering all restrictions, including silence areas, noise impact on housing, NOx deposition and the regional LOFAR installations
- Adaptation of the spatial plan from agricultural to industrial area
- Alternative for local salt plant is to install a brine transport line to Zuidwending or Harlingen; then there can be no mutual benefit of using power plant waste heat for salt production

The feasibility of obtaining all permits is considered uncertain; there are many possibilities for objections and appeal. The total time to permits is estimated at more than 3 years, excluding all appeal options.

11.5 Impact on region

11.5.1 Repeat potential

In the existing Groningen caverns, several of the Heiligerlee caverns can be used; their volume allows for more than 300 MW of CAES plants, perhaps even 2 x 300 MW installations per cavern, while still observing the maximum pressure difference of 10 bar per day.
The Zuidwending area in itself is more suited for CAES because of the more shallow salt layers. But first additional mining would be required in order to excavate enough volume at lower depth.
Both areas can accommodate several CAES units, which could share certain facilities such as grid or gas connections. The economic impact of a larger number of storage facilities has not been calculated so far, but the first order estimate is that the overall conclusions will remain intact.

The Hooghalen salt dome is large enough to accommodate a series of caverns. Development of that area first depends on finding a company interested in mining the salt, in combination with creating caverns suited for CAES (dimensions, piping). It secondly depends on obtaining the permits to create the caverns in more sensitive areas.

11.5.2 Landscape impact

The impact of CAES on the landscape is determined by the power plant required. This industrial facility is ideally situated in an industrial area which allows building of higher elements for cooling or emission of flue gases and noise emissions. The impact of the caverns is limited to the temporary installation required for salt mining, during 1-3 years per cavern. Wellheads are allowed quite close to the built environment.
Surface effects of underground storage are considered very limited, provided normal operating conditions are followed (see 1.2.3.)

11.5.3 Economic benefits

This study has not analyzed in detail the economic benefits for the region. The majority of economic benefits is created in trading rooms of the CAES operator. Operating and maintenance of the plants will create some employment, while construction of the caverns and the power plant will result in temporary employment, e.g. construction works or civil works.
Creating a series of new caverns and one or more CAES power plants in the Hooghalen region may create a significant number of jobs in Drenthe.
Other economic benefits include legal dues and annual tax payments.

Most core equipment required for CAES plants (compressors, expanders, heat exchangers, etc) will be supplied by companies from other regions and will therefore contribute only marginally to local employment or improvement of the knowledge level.

11.6 Development plan

At the moment, there is insufficient drive to start the development of a CAES plant. This relates entirely to the low expected income in two out of three power market scenarios.

The essential follow up activity is to monitor the power market developments, and the resulting differences in day-night tariffs. At the same time to monitor developments with respect to pricing of reserve power (capacity pricing), which may support business case for CAES.
On the technological side: monitor the German ADELE project and achievements in large scale energy storage with use of heat storage.

For Drenthe, it can be of interest to further study the creation of caverns in the Hooghalen salt layers, but the CAES potential is second to the direct economic benefit. Drenthe could contact Akzo Nobel, Nedmag or Frisia to discuss such developments.

REFERENCES

[Agraval 2011]
Agraval, P. et al. (Sandia National Laboratory). Characterization and assessment of novel bulk storage technologies, a study for the DOE Energy Storage System Program. Sandia report SAND 2011-3700. May 2011.

[Bullough 2004]
Chris Bullough (ALSTOM). Presentation: AA-CAES: Integration of Wind Energy. Alstom Power Technology Centre (UK), November 2004.

[Bieber 2010]
Mathilde Bieber (General Electric Global Research), Roland Marquardt, Peter Moser (RWE Power AG). Presentation: The ADELE Project - Development of an Adiabatic CAES. Berlin, November 2010.

[Bieber 2011]
Bieber, M., Marquardt, R., Moser, P. Presentation: Storage Technologies compensating for fluctuating power generation, VGB PowerTech 6/2011.

[Crotogino 2001]
Crotogino, F., Mohmeyer, K.U., Scharf, R. Huntorf CAES: more than 20 years of successful operation. Meeting, Orlando, Florida, USA, 15-18 April 2001.

[Daly 2001]
J. Daly et Al. CAES – reduced to practice. Proceedings of ASME TURBO EXPO 2001. New Orleans, Lousiana, USA, 4-7 June 2001.

[Del Turco 2009]
P. Del Turco et al. Turbomachinery solutions for advanced adiabatic compressed energy storage. EESAT proceedings. Seattle, 2009.

[Knoke 2002]
S. Knoke (Energy International, Inc). EPRI energy storage handbook: Compressed Air Energy Storage (CAES) Chapter. December 2002.

[EPRI 2004]
Energy Storage for Grid Connected Wind Generation Applications. EPRI-DOE Handbook Supplement. Report 1008703. December 2004.

[PE 2011]
http://www.power-eng.com/articles/print/volume-112/issue-6/features/intermittent-wind-problems-and-a-possible-solution.html

[Radgen 2010]
P. Radgen et Al. The economics of compressed air energy storage under various framework conditions. Paper presented at PowerGen Europe, Amsterdam, 8-10 June 2010.

[RidgeEnergy 2005]
The economic impact of CAES on Wind in TX, OK and NM. Final report for Texas State Energy Conservation Office. June 27, 2005.

[RWE 2010]
RWE. ADELE - Adiabatic compressed-air energy storage for electricity supply. Brochure, January 2010.

[Tuschy 2004]
I. Tuschy, R. Althaus, R. Gerdes, P. Keller-Sornig. Entwicklung der Gasturbinen in Luftspeicher Technologie, VGB PowerTech 4/2004.

[Zunft 2006]
S. Zunft, C. Jakiel, M. Koller, C. Bullough. Adiabatic Compressed Air Energy Storage for the Grid Integration of Wind Power. Six international work-shop on large-scale wind integration and transmission network for offshore wind farms. Delft, the Netherlands, 26-28 October 2006.

APPENDIX I ADDITIONAL OPTIONS FOR CAES PLANTS

In this the following paragraphs additional options that can be applied in a CAES concept are discussed:

- Near-isothermal compression/expansion
- Integration with Concentrating Solar Panels (CSP)
- Integration with district heating or industrial processes
- Use of water hydraulic pressure
- Under water air storage
- Adsorption enhanced air storage
- Liquid air storage.

As alternative to the air concepts a so called “Surface-Cavern water displacement” concept is discussed.

The options have been included in this appendix for information only; they do not represent at the moment potential improvements for the CAES plant subject of this study, both because they are not mature enough (their advantages have to be demonstrated in practice) and because they could not be interesting for the considered locations:
Assessment: it is a never-applied concept and may face several difficulties in real implementation.

Near isothermal compression/expansion

The most efficient compression process is the isothermal one. In real process a near isothermal compression can be achieved by compressing at sufficiently slow rate, allowing the gas to have the time to dissipate the heat to the environment. Similarly during expansion the air is expanded slowly; heat is recovered from the environment to keep the gas temperature constant during expansion.
If the heat dissipated during compression is totally recovered during expansion 100% efficiency is theoretically possible, without the need of additional fuel. In practice, however, energy losses are unavoidable therefore the real process is called near-isothermal.
The power output of the expander can be enhanced by using an external heat source (waste heat, solar heat, etc) during near-isothermal expansion, keeping the gas temperature at values above the ambient temperature. This would result in the advantage of a smaller expander for the same output.

Integration with Concentrating Solar Panels (CSP)

An interesting option is using heat collected with solar panels to heat the gas before the expander. This would results in reduced fuel consumption since the use of CSP panels can bring the air temperature up to 400-600 °C.

Such an integration reduces fuel costs but introduces additional investment cost due to the solar panels and the heat transfer additional systems. Also the flexibility is expected to decrease sharply if the system is depended on availability of the sun and inertia of the CSP system. Complete fuel start-up could increase the level of flexibility.

Assessment: it is not economically feasible for regions of north Europe like The Netherland;

Hydraulic compensation with water

The air can be compressed also by means of water; in fact if the well is beneath the ground, the pressure head of a water column can be applied to pressurize the air into the reservoir instead of using a compressor. Pressurization therefore happens naturally by means of gravitational force of the water. During off-peak periods the electricity can be used to pump water out into a surface storage (e.g. a lake). The efficiency of such a system is not expected to be very different from the typical CAES. One advantage is that the air pressure at expander inlet remains almost constant. Water, on the other hand, can introduce additional problems in operation. Especially if the reservoir is a salt cavern – salt can dissolve in water resulting in variation of the cavern volume; also, the water gets salty and this will negatively affect the lifetime of metal equipment (i.e. the water pump).

Assessment: it has the only advantage of keeping the system at constant operating pressure with respect to typical CAES. Moreover, circulation of water in the cavern introduces additional problems related to salt dissolution;

Under water air storage

A similar concept to the "hydraulic compensation" that uses the hydraulic pressure of water can be implemented in the sea or in a lake, by means of large air containers situated underwater. The pressure inside and outside the air container is always equal therefore the walls of the containers do not need to be thick – theoretically simple air balloons could be used in this application.
An advantage is that air is injected and withdrawn always at the same pressure.
This type of options is only suitable for locations near the sea or deep lakes, however the cost associated with underwater reservoirs and equipments could represent an obstacle to its realization.

Assessment: this option it is not interesting for the Groningen and Drenthe regions since salt caverns are available there;

Use of waste heat for district heating

As seen in some of the previous concepts layouts the compression produces heat that must be removed with intercoolers to increase the compressor's efficiency. An option is that of using this

heat for district heating or for industrial processes. The intercooling should be therefore designed to to be integrated in a district heating system.
The disadvantage is that the compression is intermittent therefore it doesn't represent a constant and well controllable source of heat. This problem could be (partially) solved by adding a heat storage facility. Also, storage is mostly at night, when heat demand is low.
The most important aspect is that the plant must be in the vicinity of a residential or industrial area that would make use of this heat. This aspect strongly depends by the location of the available reservoirs, thus this option must be considered case by case.
The positive aspect is that additional revenues can come from the heat delivery. However, also the CAPEX and the OPEX of the plant will be higher.

Assessment: depending on the location of the CAES plant it can be a real option. However, this option does not influence the main conclusion of the current study and can be considered later on, when this study will be developed in further details;

Adsorption enhanced air storage
This technology works by allowing compressed air to come into contact with a chemical adsorbent (e.g. zeolytes) that adsorbs gas molecules into a solid surface at certain pressure only to release it again when the pressure is reduced. The idea is that this can dramatically reduce the storage space sizes required for traditional CAES.
This technology has the potential to reduce and increase the efficiency of CAES but is at very early stage of development and much R&D is still needed to prove its technical and economic feasibility [Agraval 2011].

Assessment: is at very early stage of development and much R&D is still needed to prove its technical and economic feasibility;

Liquid air storage
Liquid air energy storage uses liquefied air as the storage medium, which provides at least ten times greater storage density than air stored as a gas. Liquid air storage does not rely on geologic formations and can therefore be constructed virtually anywhere.
This technology is inherently expensive in both equipment and installation. The engineering issues of this technology are not completely addressed and more R&D is needed to bring to pre-commercial stage [Agraval 2011].

Assessment: this concept it is not applicable for salt caverns. Moreover the engineering issues of this technology are not completely addressed.

Surface-Cavern water displacement

Underground caverns are interesting also for another aspect rather than being large volumes available at low cost. The cavern are situated usually many meters underground (400-1000 m) therefore they result in significant height to use the force of the water as it happens in typical hydro plants. This could be especially interesting in flat countries like The Netherlands.

The connection string between surface and reservoir could be used by letting water flow into the reservoir and use its kinetic energy in a water turbine underground. During off-peak hours water is pumped back on the reservoir at surface level (e.g. lake, river).

This concept has however some disadvantages:

- the water turbine must be placed underground, and this introduces significant additional costs,
- a surface reservoir for the water has to be created if natural reservoirs are not available,
- in case of salt caverns the salt can dissolve in water affecting the volume of the cavern,
- if salt dissolves in water it get salty, this create problems in the water turbine (reduced lifetime) and in the reuse of water (reinjection in rivers not possible for example).

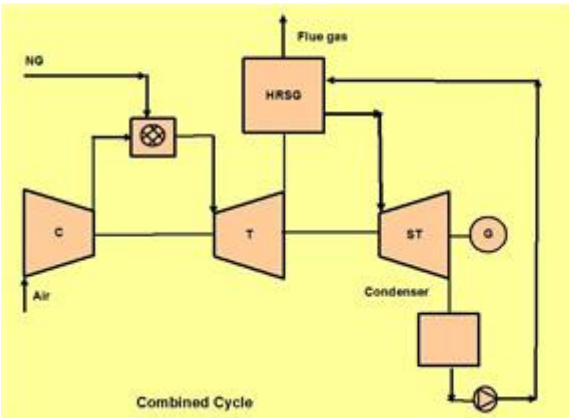
On the other hand this plant configuration is more similar to typical Pumped Hydro Storage (PHS), hence with similar advantages in term of flexibility.

Assessment: this concept is not mature enough and much research is still needed to bring it from concept to real application.

APPENDIX II SPENCE DESCRIPTION

SPENCE® means simulation of processes for energy conversion and electricity production.

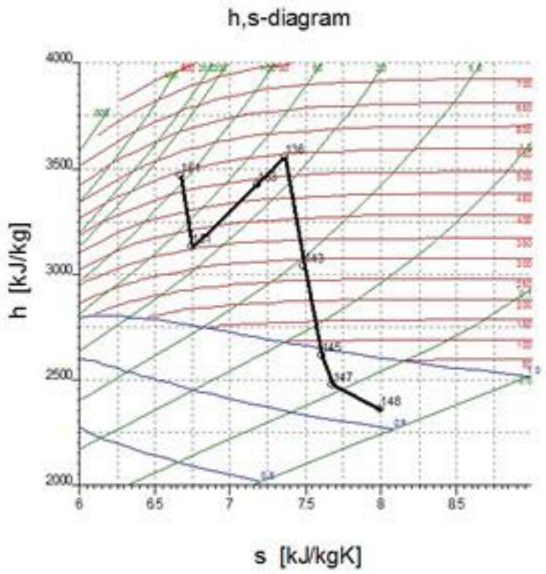
KEMA has developed a software package called SPENCE® for simulation of processes for energy conversion and electricity production. SPENCE® is intended to support thermodynamic and chemical engineers employed within electricity companies or industry.
SPENCE® supports are used in: system and feasibility studies basic design reviews process optimization upgrading and re-powering exergy analyses technical and functional specifications development of on-line conditioning monitoring modules.
SPENCE® is a static flow sheet simulator based on thermodynamics to determine the technical data and merits of energy conversion systems, including: efficiency, environmental, impact, cost/benefits.

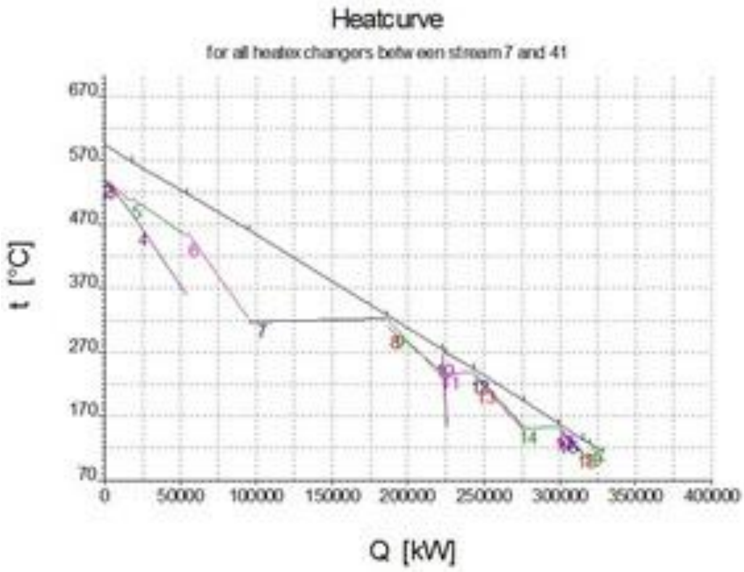


Developed in 1982, the program has been continuously improved during 25 years of research activities in improving the processes of electricity production.
The program is extremely flexible, missing equipment can easily be added to calculations. In design calculation with the program the design values can be stored and used again in part load calculation. Results are presented in tables and in graphs. Also, the process data can be exported to the graphical interface GRASP, which allows plotting flow sheets on large plotters.
In the program, libraries are included for gases, water, steam, fuels and solids. For water-steam the Industrial Standard IAPWS-IF97 for the thermodynamic properties and supplementary equations for other properties are applied. For gases non-linear behavior can be considered.

Program for optimization of energy conversion processes
With the program several system studies have been carried out, such as the impact of CO2 capture in existing power plants like IGCC, PC and NGCC. In the UPSWING project, funded by EC, the integration of municipal waste incineration in existing PC boilers has been carried out.

In the NextGenBioWaste project, also funded by EC, several studies to improve the efficiency of Waste to Energy (WtE) plants have been carried out, for example applying increased steam parameters, reducing oxygen content, integration of steam cycle of WtE plant with steam cycle of combined cycle plant, applying dry ash removal and analysis to predict location of air in-leakage.
With SPENCE® the cold end system of power plants can also be analyzed. The influence of changing cooling water conditions has been determined for several power plants.
With SPENCE® detailed tailor-made models of HRSG have been constructed to verify the given guarantee values for HP and LP steam production. In that case the non-homogenous flue gas temperatures between each heat exchanger section will be taken into account.



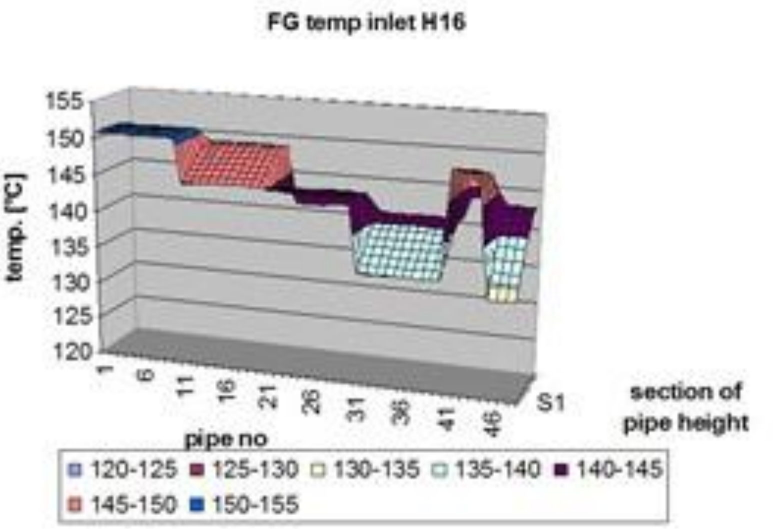


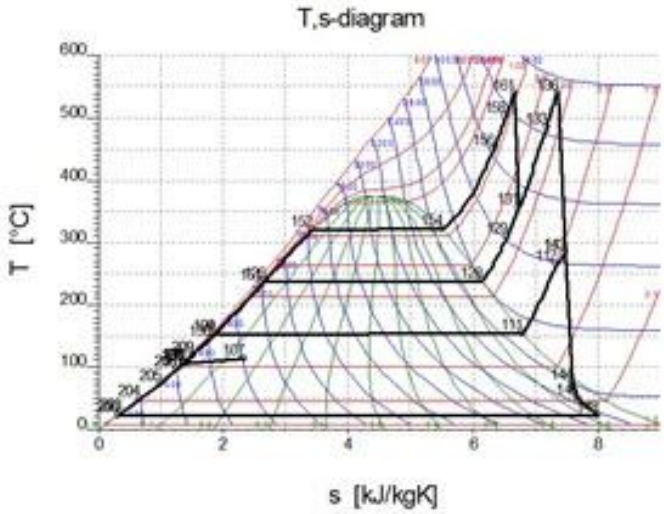
Other examples of application are coal firing and gasification, gas turbine combined cycles, feasibility studies, design reviews and other applications such as combined cycles with desalination.

Plant design and performance calculations

With the program also integrated correction curves can be constructed of complicated units composed with equipment delivered by different manufacturers and only provided with correction curves for the different equipment. This has been done for several Combined Heat and Power (CHP) plants based on gas turbines.
For a combined heat and power plant with desalination of water a special cost allocation model for the products have been developed, using special exergy functions of SPENCE.
For several clients integrated models are made with an interface with DCS systems to predict the performance of the plant based on design and actual ambient conditions.

With the program the impact of steam and or heat delivery on the electricity generation of power plants and waste to energy plants have been carried out to determine the heat and or steam price.

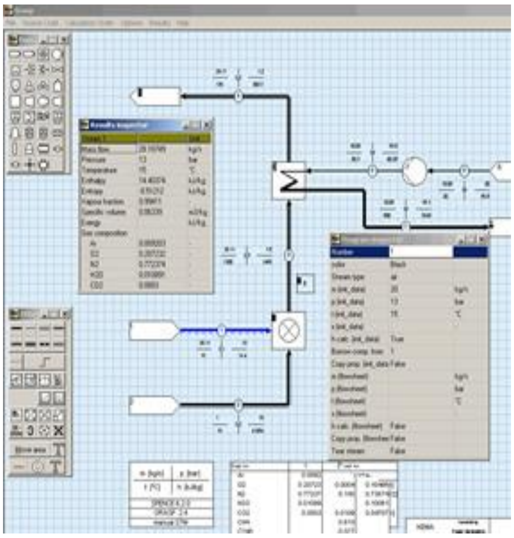




On-line process calculations to control operation processes

The basic libraries of SPENCE® have been translated and implemented on the process computer of the 265 MWe IGCC “Prins Willlem Alexander” power plant in Buggenum. They are used for on-line process calculations to control the coal gasification process.

To determine the influence of co-firing of biomass in coal fired power plants very detailed burner models have been developed. With the models the limitations of 5 pulverized coals (PC) fired boilers were investigated considering co-firing of biomass up to 25% on energy basis.



A special version of SPENCE has been developed to generate models for on-line calculation on power plants. A model of a combined cycle is implemented at a plant in Hong Kong and a model of a coal fired power plant with co-combustion of biomass is implemented at Amercentrale.

APPENDIX I DETAILED SCENARIO DESCRIPTION

i. Development of the installed generation capacity

The assumptions used by KEMA on the development of electricity generation capacities in the core region are based on individually known power projects until 2020. After 2020 typically no reliable information on projects is available. Therefore capacity expansion was made using generic power plants. These generic power plants were being added to the system to meet the overall capacity figures per technology (see detailed explanation in the scenarios below).

Business as Usual: the development of installed capacities in the Business as Usual scenario is largely based on the projections of the ENTSO-E System Adequacy Forecast 2010. In particular, the Scenario B has been made the basis for assumptions regarding capacity development. The Scenario B of the ENTSO-E SAF is a best estimate of TSOs regarding future capacity additions. The Scenario B extends until 2025. Beyond these projections KEMA assumes capacity additions to keep the operational reserve margin constant. KEMA proposes new conventional capacities for

- France on natural gas fired CCGTs and nuclear units, for
- Germany and the Netherlands on a mix of hard coal fired steam units and natural gas fired CCGTs, and for
- Belgium on a mix of natural gas fired CCGTs, hard coal fired steam and nuclear units.

Renewable energy sources are expanding in the Business as Usual scenario, but below the levels envisaged in the National Renewable Energy Actions Plans. Beyond 2025 only very minor capacity additions were assumed.

Nuclear Moratorium: the overall capacity development in the core region is in absolute terms identical to the Business as Usual scenario. The difference is the composition of the generation park with a lower overall share of nuclear capacity. The largest changes compared to the Business as Usual scenario have been made to the German nuclear fleet. In 2015 only half of the nuclear capacity in 2010 were still operational (~ 10 GW), in 2022/2023 the last nuclear installations are being shut down. For Belgium no new nuclear power plants were assumed. Instead necessary capacity additions were made based on a mix of hard coal fired steam units and natural gas fired CCGTs. For France a reduction of the standard lifetime of the older nuclear units (900 MW class) from 60 to 50 years was assumed. The shortfall was replaced exclusively by natural gas fired CCGTs. For the Netherlands no changes were assumed compared to the Business as Usual scenario.

Sustainable Development: the development of installed capacities in the Sustainable Development scenario is largely based on the projections of the ENTSO-E System Adequacy Forecast 2010. In particular, the Scenario EU 20-20-20 has been made the basis for assumptions regarding capacity development. The Scenario EU 20-20-20 of the ENTSO-E SAF is the based on the ambitious EU environmental and climate policy goals and incorporates the National Renewable

Energy Action Plans. The Scenario EU 20-20-20 extends capacity until 2020. Beyond these projections KEMA suggested a further growth of renewable energy sources up to their technical potential. Except for Belgium no new conventional generation sources were needed beyond 2020 to keep the operational reserve margin constant. Due to overcapacity in France stemming from a continued operation nuclear power plants and a huge expansion of renewable energy sources, standard lifetime for older nuclear reactors in France was reduced.

a. Germany

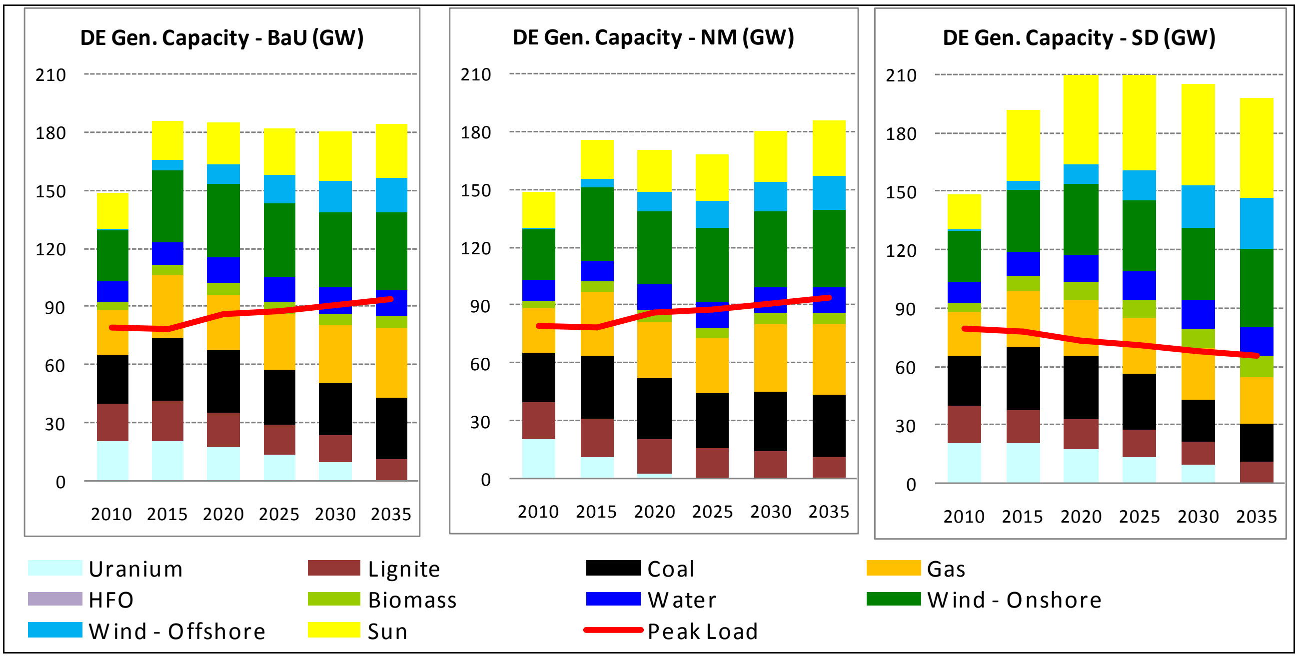


Figure 11.1: Development of installed capacity vs. peak load in Germany/main scenarios

Source: entso-e, KEMA

b. France

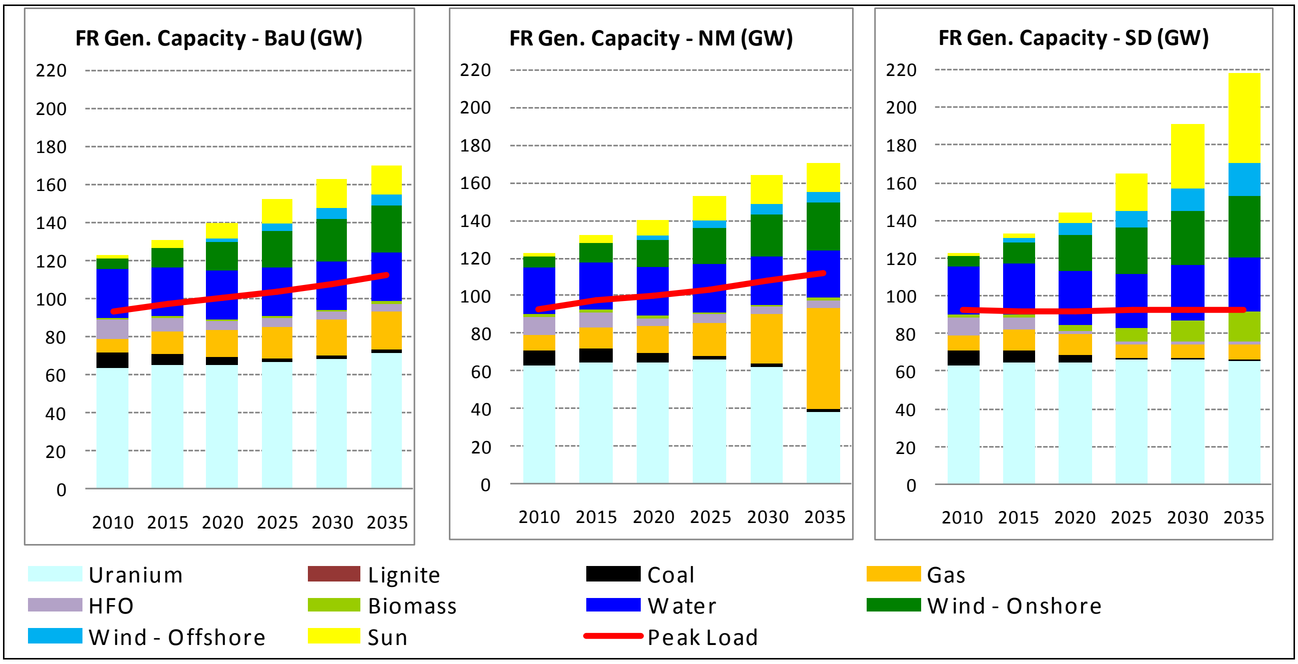


Figure 11.2: Development of installed capacity vs. peak load in France/main scenarios

Source: entso-e, KEMA

c. The Netherlands

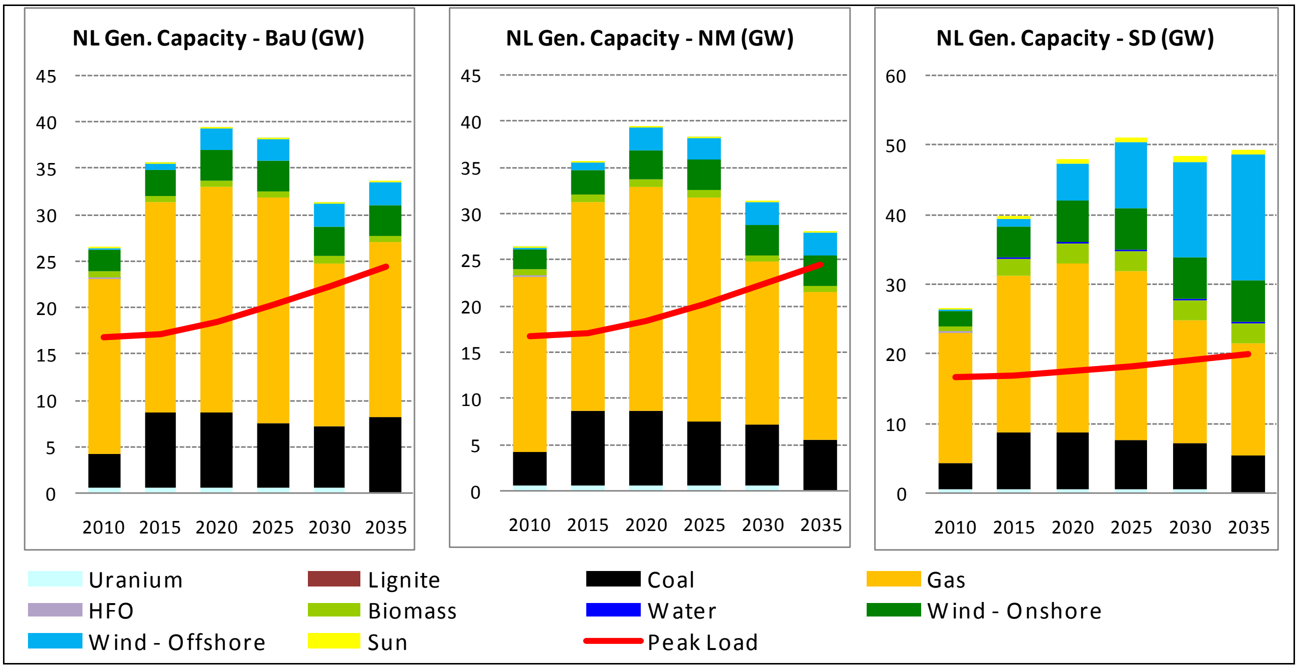


Figure 11.3: Development of installed capacity vs. peak load in the Netherlands/main scenarios

Source: entso-e, KEMA

d. Belgium

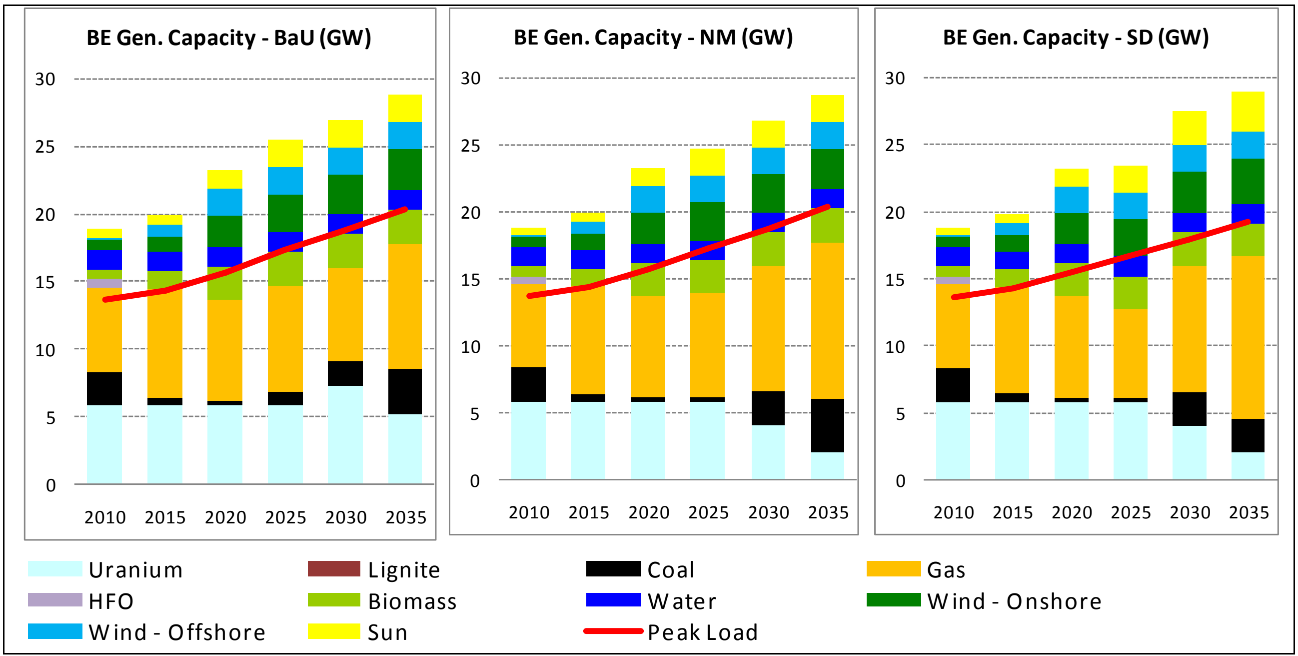


Figure 11.4: Development of installed capacity vs. peak load in Belgium/main scenarios

Source: entso-e, KEMA

Detailed data tables with the country specific generation capacities are provided in 0. **APPENDIX** II: Detailed Data-Tables.

Due to the limited size of the Luxembourg electricity system and its partial inclusion in the Belgian and German (Amprion) control areas (CCGT Esch sur Alzete in the ELIA control area, PS Vianden in the Amprion control area), the Luxembourg system is integrated into the German system.

ii. Development of consumption and demand

We have prepared forecasts on total annual electricity consumption as well as peak load for the whole North West European region until 2040. We use ENTSO-E's 2010 energy consumption and peak load values as basis for our development scenarios for the North West European region. The demand forecast is based on net electricity consumption already including grid losses, but excluding pump storage consumption and consumption of generating auxiliaries ("power plant own consumption"). For developing the growth assumptions for the Base Case, we use information provided in ENTSO-E's System Adequacy Forecast 2010 until 2025 as well as information provided in national system development plans. For the period thereafter, we have extrapolated growth rates, taking into account the general likely development of the economies. We assume a flattening of the hourly load curve due to the increase of industrial consumption, which tends to have a flatter demand profile, as well as incentives to reduce peak load consumption. For the Pessimistic Case, we assume that energy demand growth is reduced by 50% compared to our

Base Case. In the Optimistic Case, we assume a higher growth rate of consumption by 50% compared to the Base Case.

In our market model, we use demand profiles with hourly granularity for each of the model years. Hence, the future hourly load profiles for 2020, 2030 and 2040 are constructed by calibrating the individual ENTSO-E's 2010 load curves in accordance with energy and peak demand growth rates over the period 2011-2040.

Energy and peak demand are expected to have the same growth rates across the modelling period 2010 – 2035. In all three scenarios energy and peak demand are expected to grow with the same growth rates. In the SD scenario France is expected to have growth rates close to 0%. In the SD scenario the German peak and energy demand is decreasing until 2035.

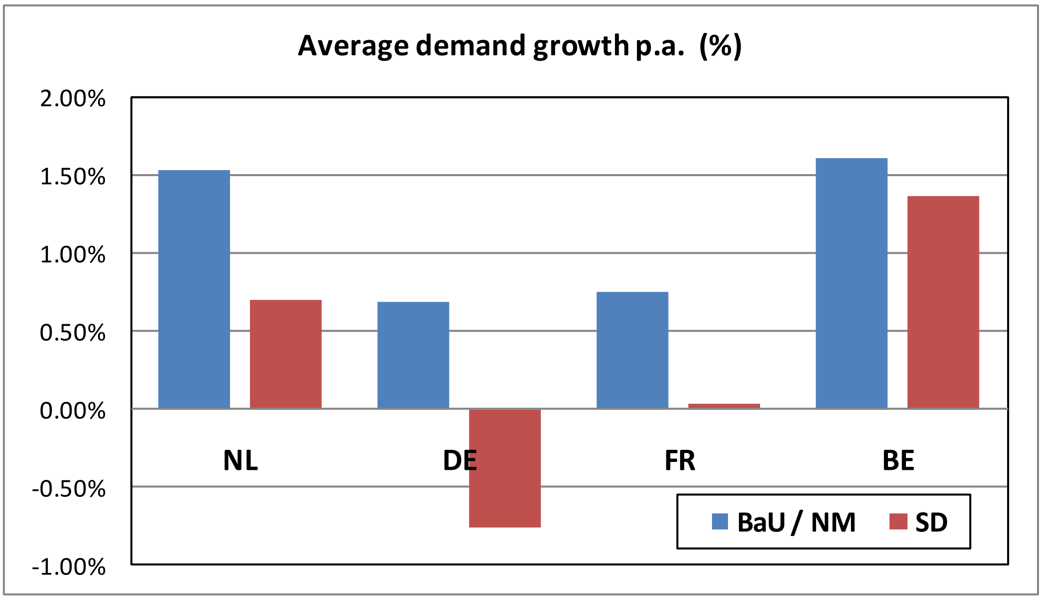
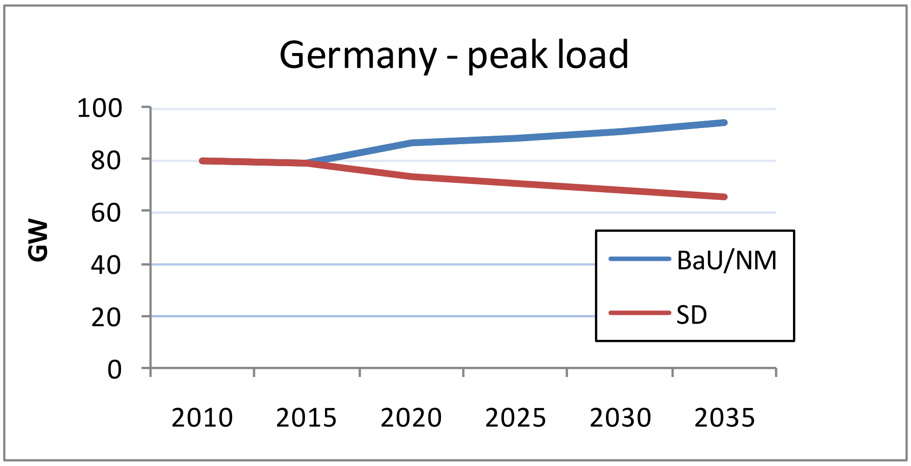


Figure 11.5: Annual average energy and peak demand growth/main scenarios
Source: entso-e, KEMA

a. Germany



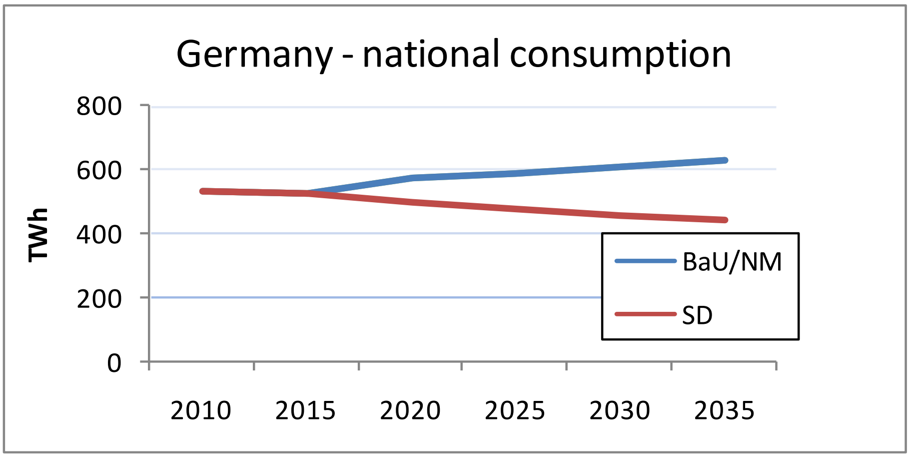
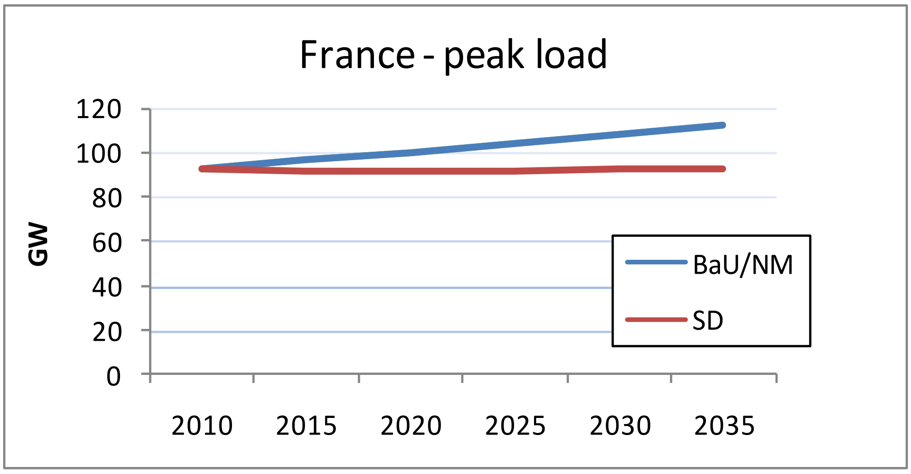


Figure 11.6: Development of peak load and national consumption in Germany/main scenarios
Source: entso-e, KEMA

b. France



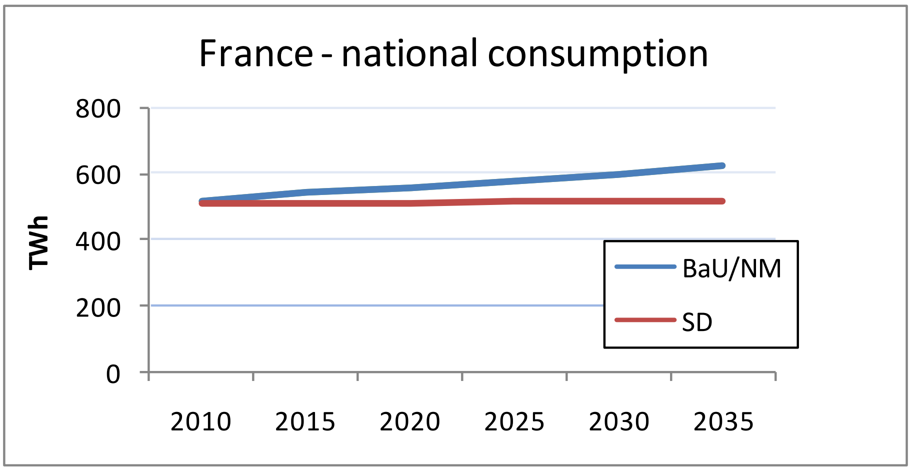
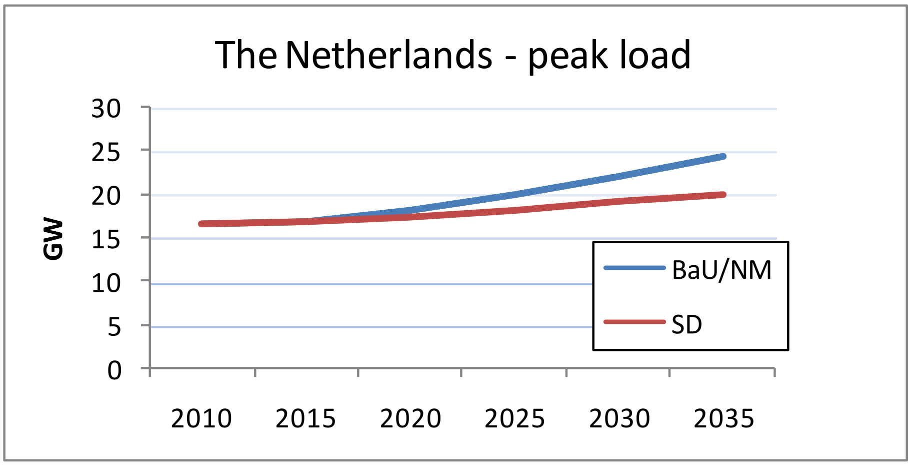


Figure 11.7: Development of peak load and national consumption in France/main scenarios
Source: entso-e, KEMA

c. The Netherlands



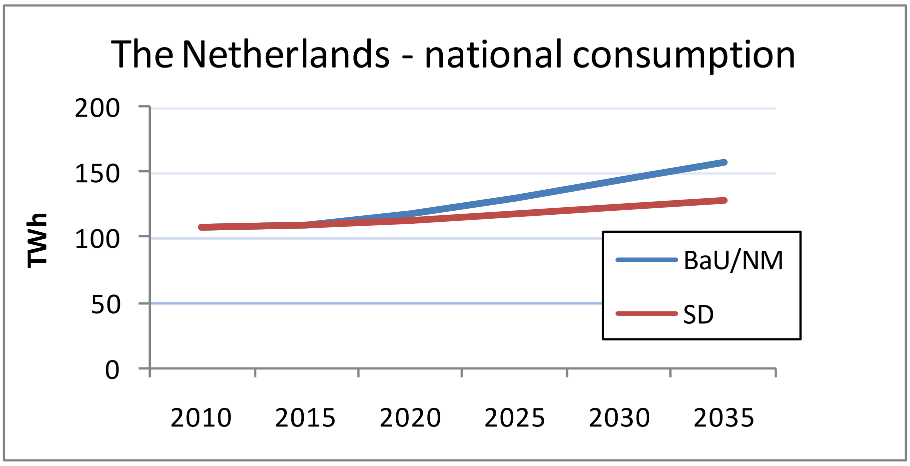


Figure 11.8: Development of peak load and national consumption in the Netherlands/main scenarios
Source: entso-e, KEMA

d. Belgium

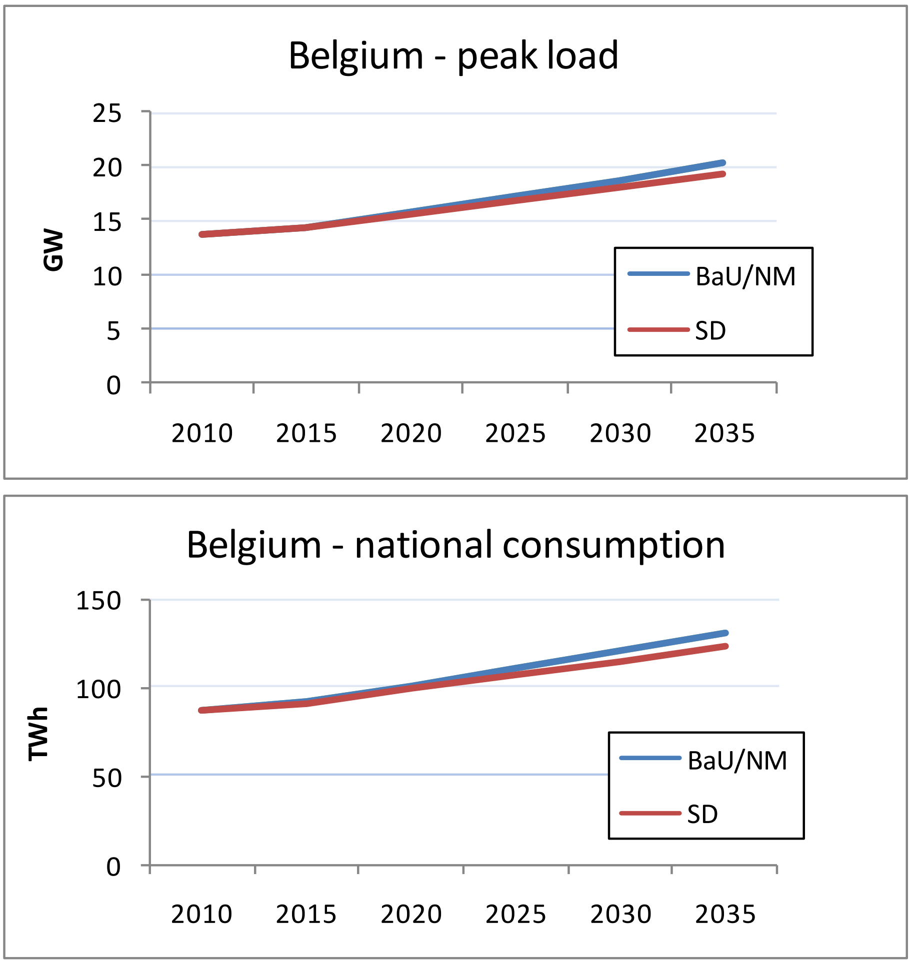


Figure 11.9: Development of peak load and national consumption in Belgium/main scenarios
Source: entso-e, KEMA

iii. Development of primary fuel prices and prices of emission certificates

All prices are shown in nominal terms. We assumed an annual inflation rate of 2,3% p.a. in line with the World Energy Outlook 2010 assumptions of the IEA.

Crude oil prices are assumed to be a driver for most other commodity prices across the modelling period. In the BaU scenario, gas prices are assumed to increase to nearly 35EUR/MWh in 2020 and above 58EUR/MWh in 2035. In NM and SD scenarios, fuel prices are expected to increase slower to nearly 54EUR/MWh and 44EUR/MWh respectively. Assumed modest seasonality of natural gas prices (125% - 80%).

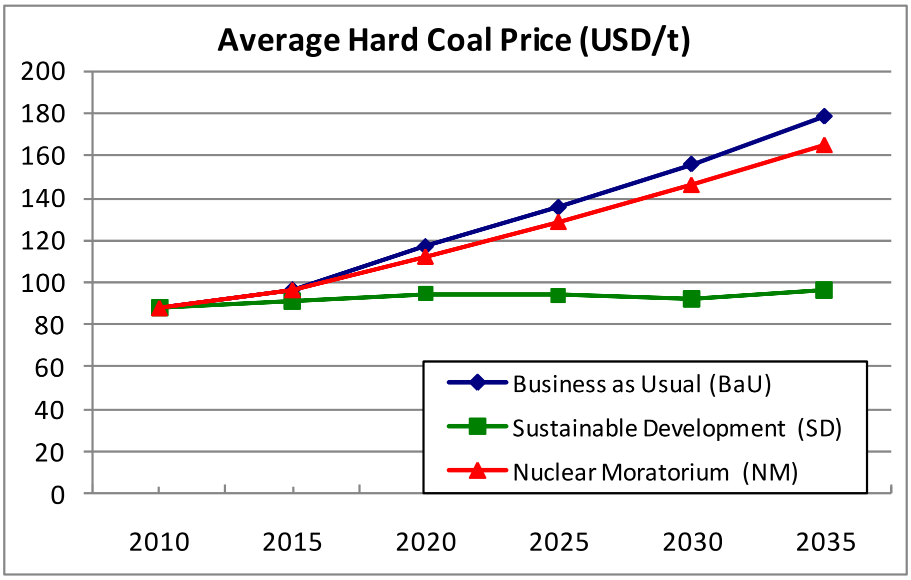


Figure 11.10: Development of crude oil prices/main scenarios

Source: IEA (WEO 2010)

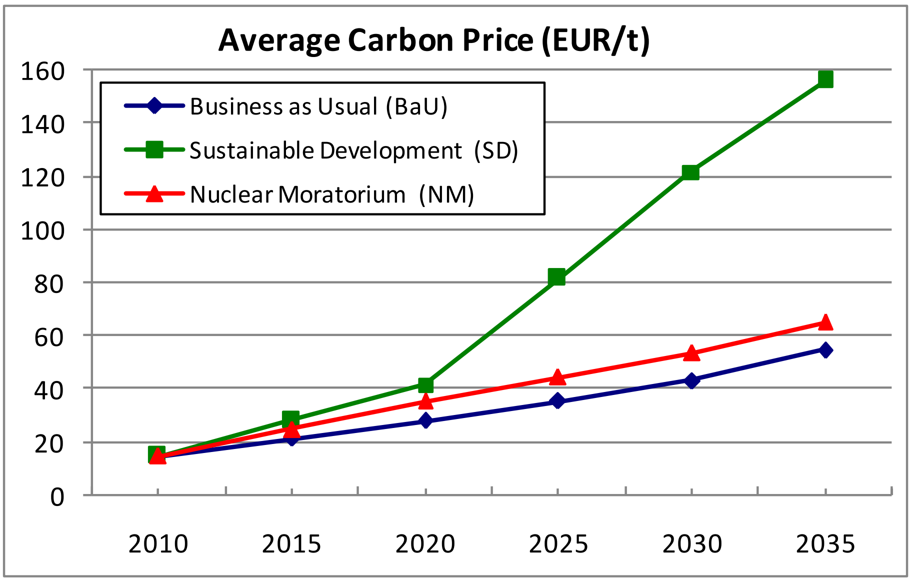


Figure 11.11: Development of natural gas prices/main scenarios

Source: IEA (WEO 2010)

International Coal prices show a broad price range across the three modelling scenarios ranging from 96USD/t in SD to 178USD/t in the BaU scenario. Local lignite is priced at a discount of 25% to hard coal prices. In all three scenarios, carbon prices are assumed to increase from 2010 onwards to nearly 55EUR/t in the BaU, 65EUR/t in the NM and 156EUR/t in the SD scenario in 2035. For carbon content of fuels, individual conversion coefficients per main type of fuel were used according to IPCC guidelines.

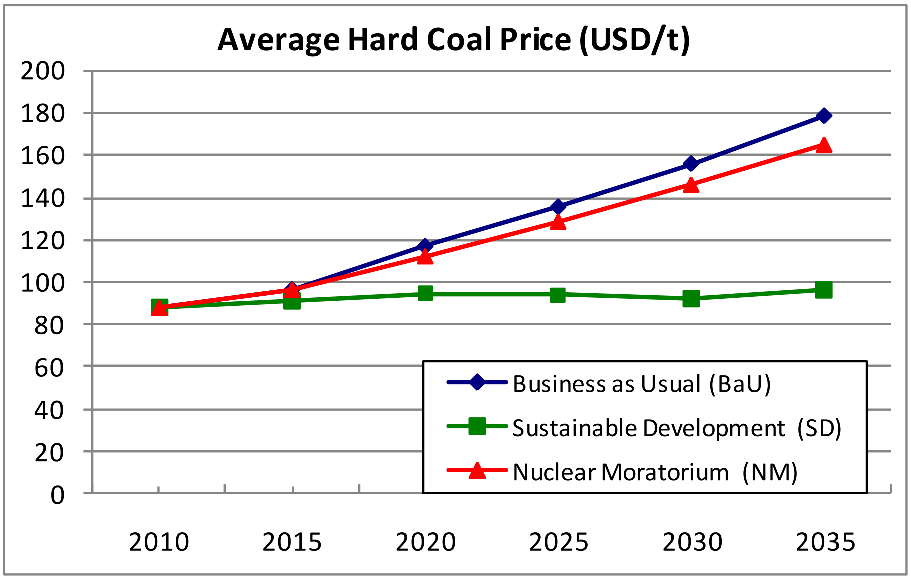


Figure 11.12: Development of hard coal prices/main scenarios
Source: IEA (WEO 2010)

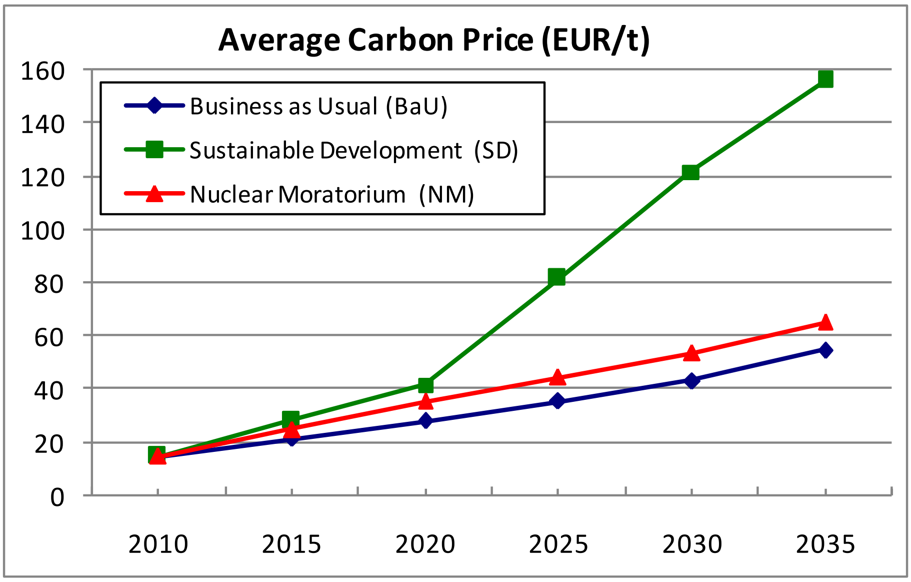


Figure 11.13: Development of emission prices/main scenarios
Source: IEA (WEO 2010)

iv. Development of grid infrastructure and interconnections

Inleidende tekst, negatief betekent …

		Bau / NM			SD	
From	**To**	**2010**	**2020**	**2030**	**2020**	**2030**
Belgium	**France**	2300	2300	2300	2300	2300
Belgium	**France**	-3400	-3400	-3400	-3400	-3400
Germany	**France**	3200	3200	3200	3200	3200
Germany	**France**	-2700	-2700	-2700	-2700	-2700
The Netherlands	**Belgium**	2400	2400	2400	3000	3000
The Netherlands	**Belgium**	-2400	-2400	-2400	-3000	-3000
The Netherlands	**Germany**	3000	3000	3000	3000	3000
The Netherlands	**Germany**	-3850	-3850	-3850	-3850	-3850
Germany	**Belgium**	0	1000	1000	1000	1000
Germany	**Belgium**	0	-1000	-1000	-1000	-1000

Table 5: Overview of NTC capacities between core countries

Source: ENTSO-E, KEMA

		Bau / NM			SD	
From	**To**	**2010**	**2020**	**2030**	**2020**	**2030**
Germany	**Czech Republic**	800	800	800	800	800
Germany	**Czech Republic**	-2300	-2300	-2300	-2300	-2300
Germany	**Poland**	0	1200	1200	1200	1200
Germany	**Poland**	-1100	-1100	-1100	-1100	-1100
Germany	**Austria**	2200	2200	2200	2200	2200
Germany	**Austria**	-2000	-2000	-2000	-2000	-2000
Germany	**Switzerland**	1500	1500	1500	1500	1500
Germany	**Switzerland**	-3500	-3500	-3500	-3500	-3500
Germany	**Norway**	2150	2150	2150	2150	3150
Germany	**Norway**	-2695	-2695	-2695	-2695	-3695
France	**Switzerland**	3200	3200	3200	3200	3200
France	**Switzerland**	-1100	-1100	-1100	-1100	-1100
France	**Iberia**	1300	1600	2000	2800	4000
France	**Iberia**	-500	-1200	-2000	-2800	-4000
France	**Italy**	2575	2875	2875	3175	4175
France	**Italy**	-995	-1295	-1295	-1595	-2595
France	**UK**	2000	2000	2000	3000	3000
France	**UK**	-2000	-2000	-2000	-3000	-3000
The Netherlands	**Norway**	700	700	700	700	700
The Netherlands	**Norway**	-700	-700	-700	-700	-700
The Netherlands	**UK**	0	1000	1000	1000	1000
The Netherlands	**UK**	0	-1000	-1000	-1000	-1000

Table 6: Overview of NTC capacities between core and satellite regions

Source: ENTSO-E, KEMA

Appendix **II: DETAILED DATA-TABLES**

	Business as Usual						Nuclear Moratorium					Sustainable Development				
	2010	2015	2020	2025	2030	2035	2015	2020	2025	2030	2035	2015	2020	2025	2030	2035
Uranium	20.47	20.47	17.46	13.39	9.54	-	10.77	2.63	-	-	-	20.47	17.46	13.39	9.54	-
Lignite	19.54	20.58	17.59	15.79	14.29	11.40	20.58	17.59	15.79	14.29	11.40	17.07	15.79	14.29	11.40	11.23
Coal	25.41	32.45	32.17	28.39	26.36	31.39	32.45	32.17	28.39	30.86	32.14	32.45	32.17	28.39	21.86	19.39
Gas	22.88	32.91	29.20	28.50	30.28	36.26	32.91	29.20	28.50	35.08	36.66	28.82	28.93	28.50	26.28	23.92
HFO	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Biomass	4.12	5.40	6.00	6.00	6.00	6.00	5.40	6.00	6.00	6.00	6.00	7.88	9.00	9.56	10.24	10.96
Hydro	10.82	11.22	13.12	13.22	13.32	13.42	11.22	13.12	13.22	13.32	13.42	12.23	14.42	14.54	14.65	14.77
Wind–Onshore	26.80	37.70	38.00	38.40	39.00	40.00	37.70	38.00	38.40	39.00	40.00	31.80	36.00	36.64	37.27	40.00
Wind-Offshore	0.40	5.10	10.00	14.10	16.00	18.00	5.10	10.00	14.10	16.00	18.00	5.10	10.00	16.00	22.26	26.42
Sun	18.10	20.00	22.00	24.00	26.00	28.00	20.00	22.00	24.00	26.00	28.00	36.10	52.50	51.75	51.75	51.75
Total	**148.54**	**185.83**	**185.53**	**181.79**	**180.78**	**184.48**	**176.13**	**170.71**	**168.40**	**180.54**	**185.63**	**191.92**	**216.26**	**213.05**	**205.25**	**198.44**

Table 7: Installed generation capacity in Germany/main scenarios in GW

Source: ENTSO-E/KEMA

	Business as Usual						Nuclear Moratorium					Sustainable Development				
	2010	2015	2020	2025	2030	2035	2015	2020	2025	2030	2035	2015	2020	2025	2030	2035
Uranium	63.19	64.79	64.79	66.39	67.99	71.19	64.79	64.79	66.39	61.90	38.28	64.79	64.79	66.39	66.39	66.39
Lignite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coal	7.97	6.25	4.54	1.66	1.62	1.51	6.75	4.54	1.66	1.62	1.51	6.25	4.04	0.34	0.34	0.23
Gas	7.88	11.37	14.05	17.25	19.13	20.33	11.49	14.05	17.65	26.33	53.53	11.37	10.61	7.83	7.83	7.83
HFO	9.65	7.40	4.73	4.39	4.29	4.29	8.01	4.73	4.39	4.29	4.29	5.74	2.25	1.27	1.27	1.27
Biomass	1.10	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.90	3.00	7.20	11.38	15.56
Hydro	25.40	25.40	25.40	25.40	25.40	25.40	25.40	25.40	25.40	25.40	25.40	27.40	28.70	28.70	28.70	28.70
Wind–Onshore	5.66	10.00	15.00	19.00	22.00	25.00	10.00	15.00	19.00	22.00	25.00	10.70	19.00	24.20	29.21	33.20
Wind-Offshore	-	-	2.00	4.00	6.00	6.00	-	2.00	4.00	6.00	6.00	2.70	6.00	9.20	11.87	17.00
Sun	1.40	3.90	8.00	13.00	15.00	15.00	3.90	8.00	13.00	15.00	15.00	2.40	5.40	19.57	33.74	47.91
Total	**122.25**	**130.31**	**139.71**	**152.29**	**162.63**	**169.92**	**131.54**	**139.71**	**152.69**	**163.74**	**170.21**	**133.25**	**143.79**	**164.70**	**190.73**	**218.09**

Table 8: Installed generation capacity in France/main scenarios

Source: ENTSO-E/KEMA

	Business as Usual						Nuclear Moratorium					Sustainable Development				
	2010	2015	2020	2025	2030	2035	2015	2020	2025	2030	2035	2015	2020	2025	2030	2035
Uranium	0.48	0.48	0.48	0.48	0.48	-	0.48	0.48	0.48	0.48	-	0.48	0.48	0.48	0.48	-
Lignite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coal	3.71	8.10	8.16	7.01	6.62	8.20	8.10	8.16	7.01	6.62	5.40	8.10	8.16	7.01	6.62	5.40
Gas	18.95	22.74	24.34	24.34	17.70	18.88	22.74	24.34	24.34	17.70	16.08	22.74	24.34	24.34	17.70	16.08
HFO	0.12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Biomass	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	2.44	2.90	2.90	2.90	2.88
Hydro	-	-	-	-	-	-	-	-	-	-	-	0.10	0.20	0.21	0.21	0.21
Wind–Onshore	2.24	2.80	3.30	3.30	3.30	3.30	2.80	3.30	3.30	3.30	3.30	4.40	6.00	6.00	6.00	6.00
Wind-Offshore	0.20	0.80	2.50	2.50	2.50	2.50	0.80	2.50	2.50	2.50	2.50	1.20	5.20	9.47	13.76	18.05
Sun	0.10	0.00	0.10	0.10	0.10	0.10	0.00	0.10	0.10	0.10	0.10	0.30	0.70	0.72	0.72	0.72
Total	**26.50**	**35.62**	**39.57**	**38.43**	**31.41**	**33.68**	**35.62**	**39.57**	**38.43**	**31.41**	**28.08**	**39.76**	**47.97**	**51.12**	**48.40**	**49.34**

Table 9: Installed generation capacity in the Netherlands/main scenarios

Source: ENTSO-E/KEMA

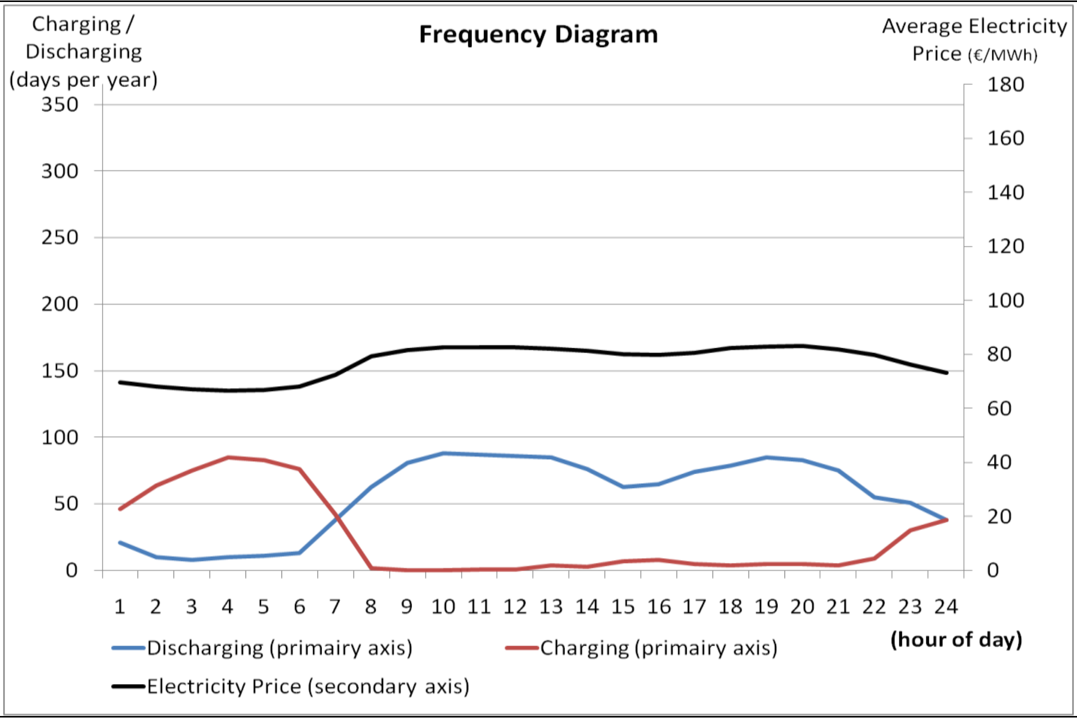
	Business as Usual						Nuclear Moratorium					Sustainable Development				
	2010	2015	2020	2025	2030	2035	2015	2020	2025	2030	2035	2015	2020	2025	2030	2035
Uranium	5.82	5.82	5.82	5.82	7.24	5.22	5.82	5.82	5.82	4.04	2.02	5.82	5.82	5.82	4.04	2.02
Lignite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coal	2.51	0.61	0.30	1.05	1.80	3.30	0.61	0.30	0.30	2.55	4.05	0.59	0.30	0.30	2.55	2.55
Gas	6.26	8.02	7.56	7.82	7.00	9.29	8.02	7.56	7.82	9.40	11.69	7.96	7.56	6.62	9.40	12.09
HFO	0.56	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Biomass	0.76	1.30	2.46	2.48	2.50	2.50	1.30	2.46	2.48	2.50	2.50	1.30	2.46	2.46	2.46	2.44
Hydro	1.43	1.43	1.45	1.45	1.45	1.45	1.43	1.45	1.45	1.45	1.45	1.43	1.45	1.46	1.46	1.47
Wind–Onshore	0.80	1.20	2.32	2.82	2.90	3.00	1.20	2.32	2.82	2.90	3.00	1.20	2.32	2.82	3.10	3.40
Wind-Offshore	0.11	0.85	2.00	2.00	2.00	2.00	0.85	2.00	2.00	2.00	2.00	0.85	2.00	2.00	2.00	2.00
Sun	0.59	0.71	1.34	2.00	2.00	2.00	0.71	1.34	2.00	2.00	2.00	0.71	1.34	2.00	2.50	3.00
Total	**18.84**	**19.94**	**23.25**	**25.44**	**26.88**	**28.76**	**19.94**	**23.25**	**24.69**	**26.83**	**28.71**	**19.86**	**23.25**	**23.48**	**27.50**	**28.96**

Table 10: Installed generation capacity in Belgium/main scenarios

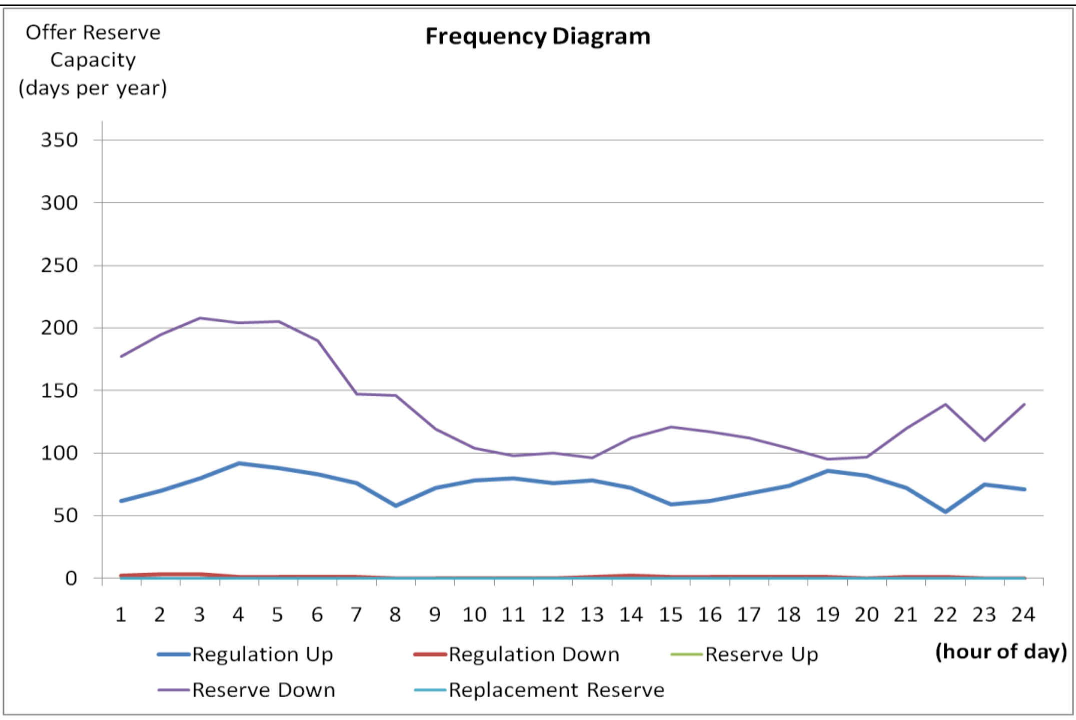
Source: ENTSO-E/KEMA

APPENDIX III EXAMPLE OF DISPATCH AND RESERVE OFFERING

Example: Business as Usual - 2025



Charging and discharging strategy expressed in the total number of days per year (left axis) and compared to the average price per hour of the day (right axis).



Reserve capacity offered per hour of the day expressed in the total number of days per year.

BIJLAGE A ALGEMEEN OVERZICHT BENODIGDE VERGUNNINGEN CAES PROJECT

Vergunning/ wetgeving	Caverne (zoutwinning)	Caverne (opslag)	Centrale (pomp+opwekking)	Gasaansluiting	Netaansluiting	Bevoegd gezag
Algemeen						
Project MER-plicht [1)]	nee	nee	ja, indien ≥300 MW cat. C22.1	nee	nee, tenzij ≥ 220kV en ≥15km cat. C 24	Provincie/ELI
Project MER-beoordelingsplicht [2)]	nee, tenzij in gevoelig gebied (cat. D.29.1)	nee, tenzij in gevoelig gebied (cat. D.29.1)	ja, project ≥200 MW cat. D.22.1	nee, tenzij ≥ 5 km in gevoelig gebied cat. D 8.2	nee, tenzij ≥150 kV en ≥ 5 km in gevoelig gebied (cat.D.24.1)	Provincie/ELI
Plan MER-plicht	nee, tenzij in gevoelig gebied (cat. D.29.1)	nee, tenzij in gevoelig gebied (cat. D.29.1)	ja, plan ≥200 MW D.22.1	nee, tenzij bij plan voor project ≥ 5 km in gevoelig gebied cat. D. 8.2	nee, tenzij plan voor project ≥150 kV en ≥ 5 km in gevoelig gebied cat D.24.1	Min ELI
Rijkscoordinatieregeling	nee	ja [3)]	nee	nee, tenzij bij uitbreiding hoofd-transportnet ≥ 40 bar en ≥ 45,7 cm	nee, tenzij ≥ 220 kV	Min ELI (coord.)/ Min IenM
Mijnbouwwet						
Opsporingsvergunning	ja	nvt	nvt	nvt	nvt	Min ELI
Winningsvergunning annex -plan	ja	nee	nvt	nvt	nvt	Min ELI
Opslagvergunning annex -	nee	ja	nvt	nvt	nvt	Min ELI

plan						
Wabo						
Omgevingsvergunning	ja [4)]	ja [4)]	ja	mogelijk	mogelijk	Min ELI / Provincie
Natuurbeschermingswet	mogelijk	mogelijk	mogelijk	mogelijk	mogelijk	Provincie
Flora en faunawet	mogelijk	mogelijk	mogelijk	mogelijk	mogelijk	Min ELI
Waterwet						
Watervergunning	ja	ja	ja	ja	ja	Waterschap / RWS
Overig						
Ontgrondingenwet	mogelijk	mogelijk	mogelijk	mogelijk	mogelijk	Provincie
Lokale vergunningen	ja	ja	ja	ja	ja	Provincie / gemeente
Emissievergunning CO2, NO_x	nvt	nvt	ja	nvt	nvt	NEA

1) lijst C uit de Bijlage van het Besluit m.e.r.
2) lijst D uit de Bijlage van het Besluit m.e.r.
3) namelijk van toepassing op opslag van *stoffen.* De opslag van gecomprimeerde lucht wordt als zodanig beschouwd
4) bovengronds deel

BIJLAGE B PROCEDURESTAPPEN RIJKSCOORDINATIE

De volgende fasen worden bij Rijkscoördinatie doorlopen:

Fase	
1	De initiatiefnemer maakt zijn plannen voor een bepaald energieproject bekend aan de minister van ELI. In de wet ligt vast welke projecten onder rijkscoördinatie vallen.
2	De ministeries van ELI en IenM bepalen of ze een ruimtelijk besluit gaan nemen en bereiden dat besluit in overleg met de initiatiefnemer en de betrokken overheden voor.
3	Bureau Energieprojecten onderzoekt samen met de initiatiefnemer en de betrokken overheden welke vergunningen en ontheffingen voor het project nodig zijn.
4	De initiatiefnemer vraagt alle vergunningen en ontheffingen aan bij de bevoegde overheden. De coördinerende minister spreekt met deze overheden een gezamenlijke planning af.
5	De betrokken overheden maken in overleg met elkaar hun ontwerpbesluiten. De ministers van ELI en IenM stellen, als daarvoor gekozen is, ook een ontwerp-rijksinpassingsplan op.
6	De ontwerpbesluiten liggen gebundeld ter inzage. In deze periode kan iedereen schriftelijk inspreken. Vaak worden een of meer informatieavonden georganiseerd, waar ook inspraak gegeven kan worden.
7	De overheden verwerken de adviezen en inspraak en maken hun besluiten definitief.
8	De definitieve besluiten liggen weer gezamenlijk ter inzage. Belanghebbenden kunnen beroep aantekenen tegen deze besluiten, meestal direct bij de Raad van State.
9	De Afdeling bestuursrechtspraak van de Raad van State doet uitspraak op de beroepen tegen een of meer van de besluiten. In geval van rijkscoördinatie mét een rijksinpassingsplan gebeurt dit in één uitspraak, binnen 6 maanden na ontvangst van het verweerschrift van de betrokken overheden.

APPENDIX III SPENCE FLOWSHEETS

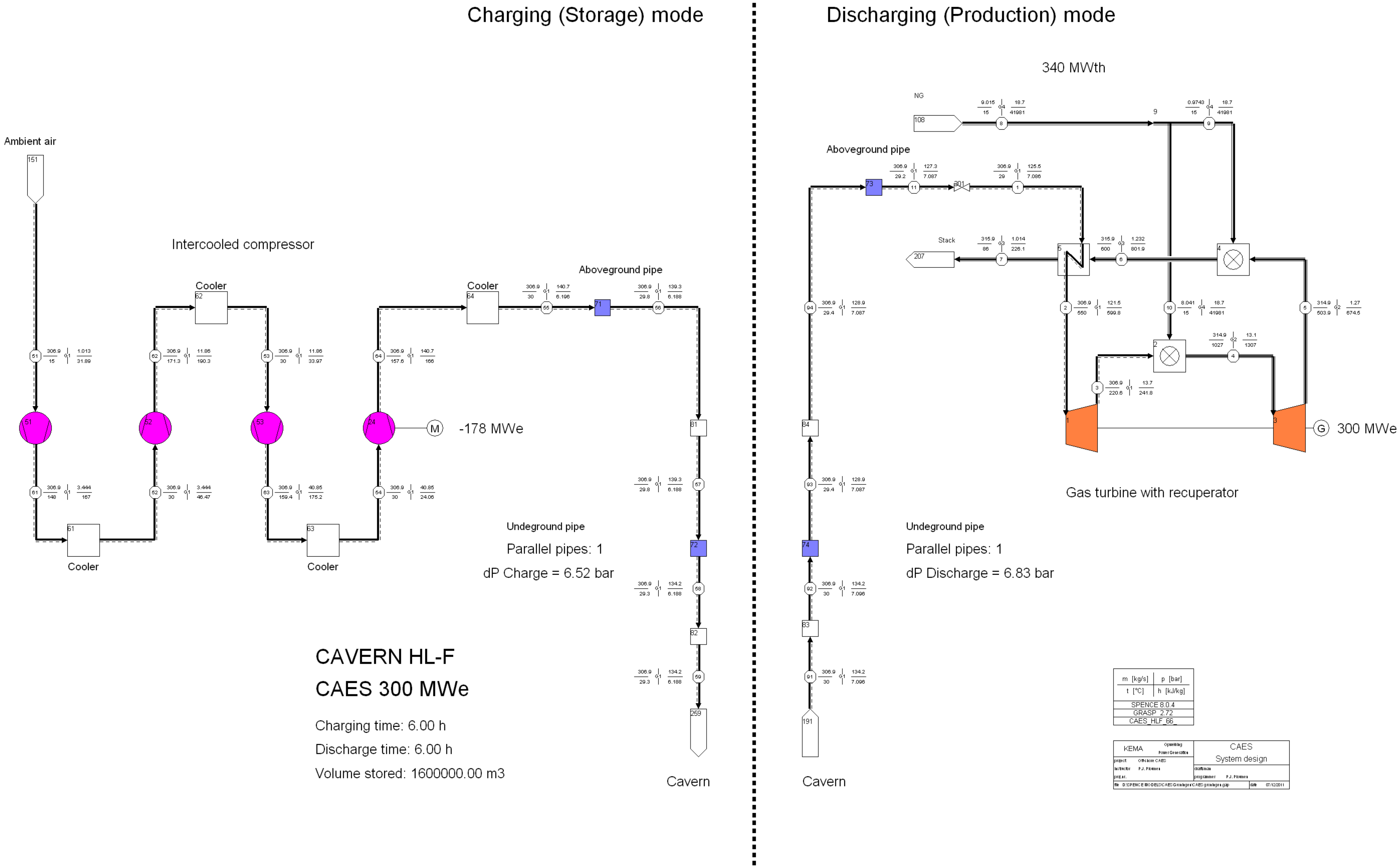


Figure A2-1 SPENCE flowsheet of case 1 (HL-F 6/6 newpipe)

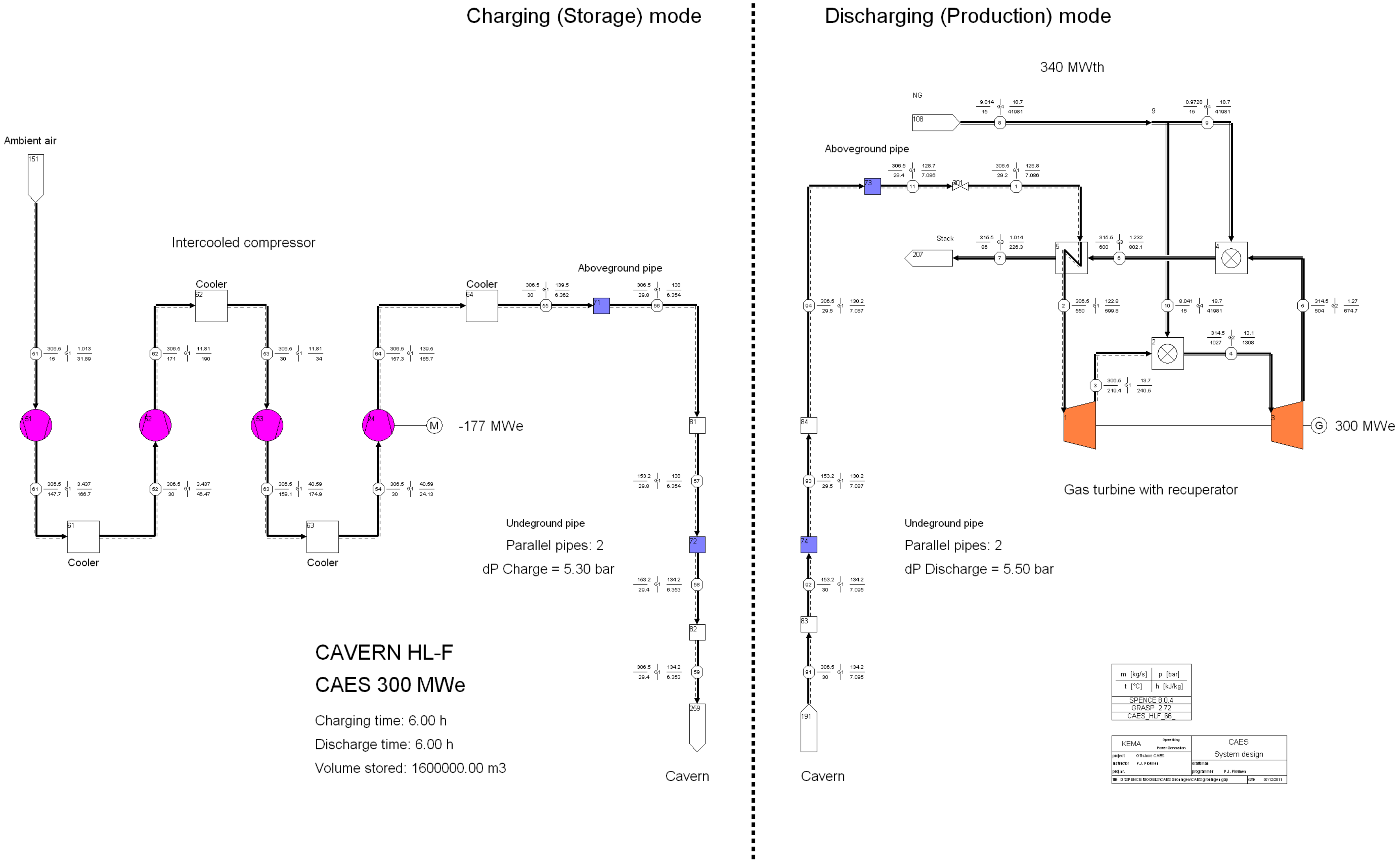


Figure A2-2 SPENCE flowsheet of case 2 (HL-F 6/6 2eqpipe)

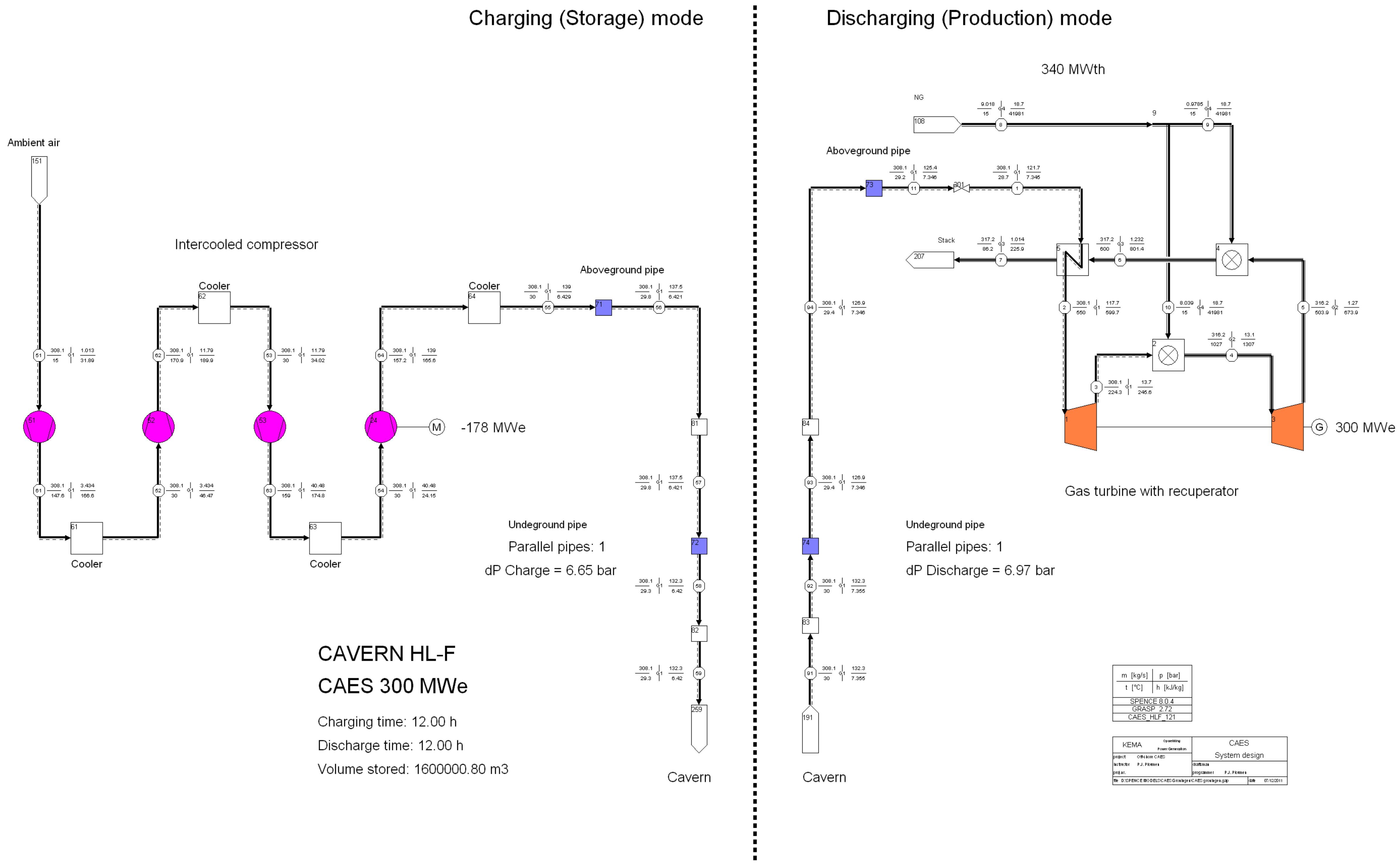


Figure A2-3 SPENCE flowsheet of case 3 (HL-F 12/12 newpipe)

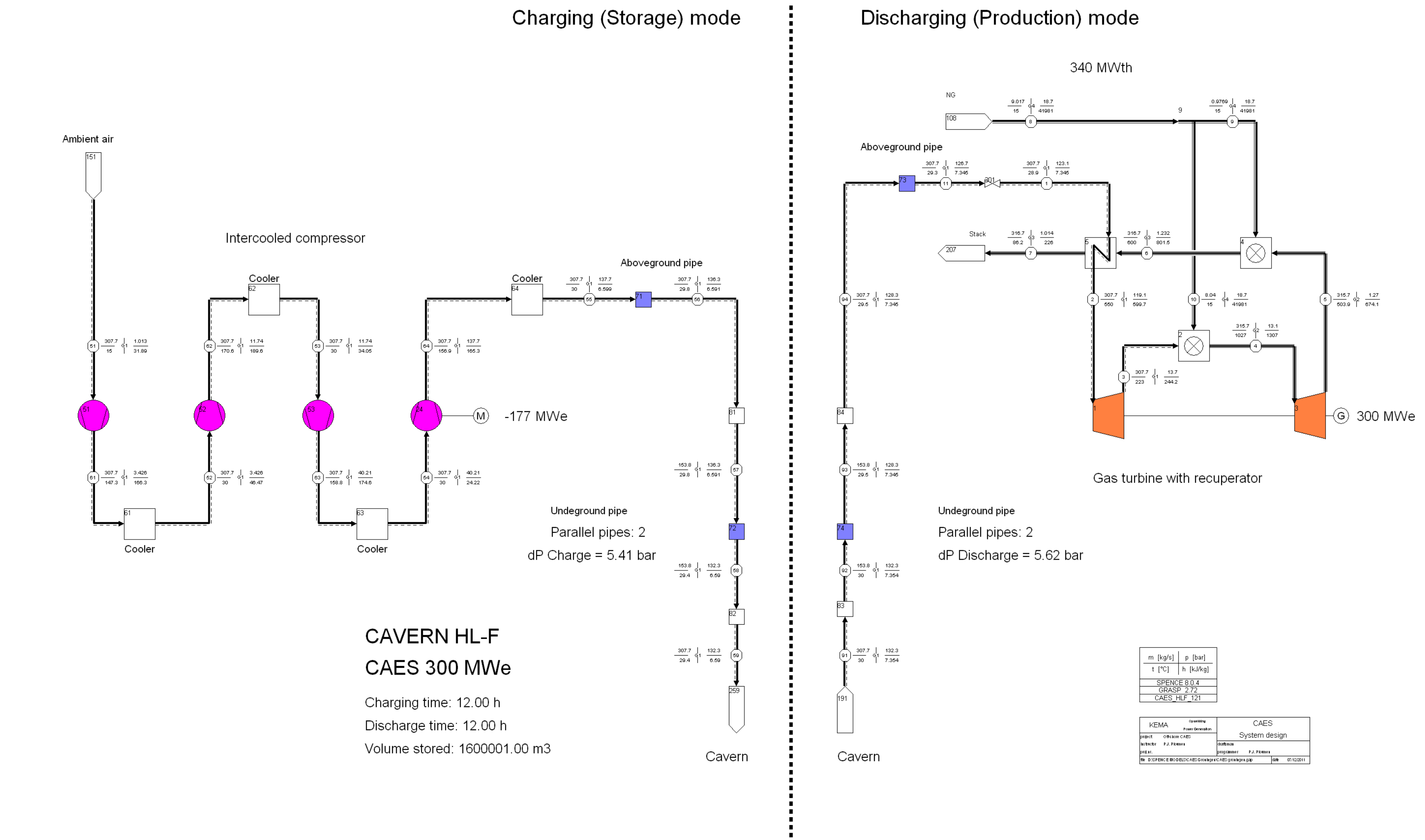


Figure A2-4 SPENCE flowsheet of case 4 (HL-F 12/12 2eqpipe)

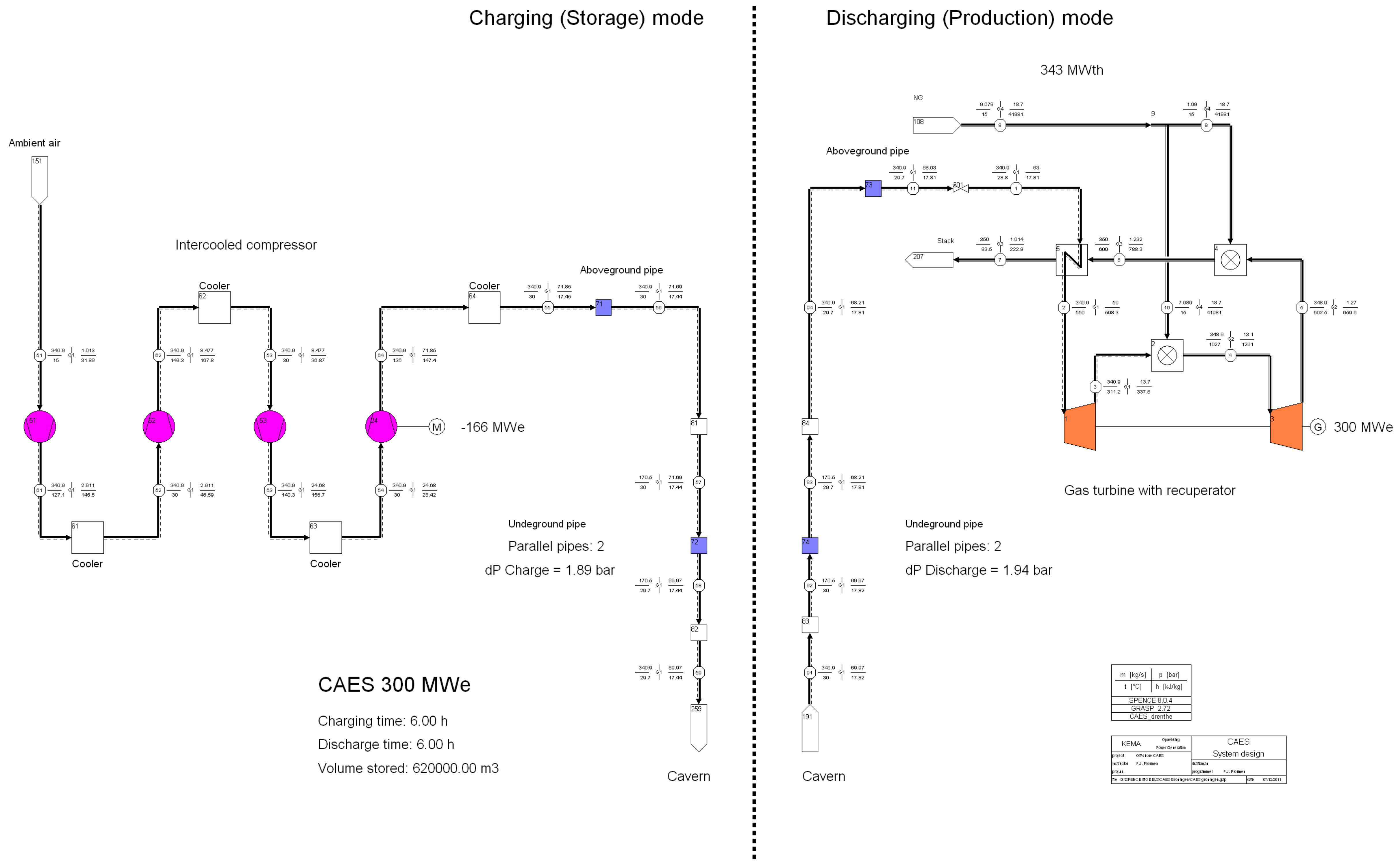


Figure A2-5 SPENCE flowsheet of case 5 (Drenthe)