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Efficient Gas Depressurisation via the EGPT Process

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ABSTRACT

This paper begins with a discussion of the opportunity for accessing the gas expansion energy which is available whenever a flow of natural gas undergoes pressure reduction. The magnitude of the global energy resource from this effect is estimated from gas consumption data and common practice in the transmission and distribution of natural gas. A developable resource in the range of 5GW is indicated, even after a major discounting of the nominal values.

The central difficulty in developing this resource is shown to lie in the large requirement for heat which accompanies power-producing pressure reduction. Different approaches taken to access gas expansion energy are discussed and a number of factors which have thus far limited the exploitation of this resource are noted.

A novel approach called Expanding Gas Power Transformation is introduced. This technique makes purposeful use of several attributes of the transcritical heat pump cycle to allow the gas heating difficulty to be surmounted without the introduction of extraneous equipment onto the pressure reduction site. The resulting pressure reduction system requires no fuel consumption whatsoever to deal with the gas heating problem and it allows the export of a substantial fraction of the expansion energy as completely carbon-free electricity. The required heat is sourced from the ambient at high efficiency by the transcritical heat pump.

A preliminary investigation of the economic feasibility shows that the EGPT approach is financially interesting in most energy cost regimes, but especially where a premium is paid for authentic carbon-free motive power. Added to this is the saving of gas and of CO_2 emissions which would otherwise have been incurred by fuel consumption for gas warming. The estimated installed cost and CO_2 effectiveness of the EGPT process are shown to compare favourably with the well established figures for onshore wind power.

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1. INTRODUCTION

Pressure reduction in natural gas pipelines is usually accompanied by a wasteful consumption of gas. Gas generally emerges cooled from the throttling valve as a result of the Joule-Thomson process. This cooling is generally undesirable, and in most cases it is counteracted by warming the gas stream prior to its depressurisation...most commonly by burning a small portion of the gas in transit. Not only does the throttling valve make gas heating necessary, but pressure reduction by throttling valve also destroys the opportunity to recover the very substantial quantity of expansion energy available from high pressure natural gas streams.

This paper presents an estimate of the global size of this resource and a brief overview of technologies put forward to exploit it.

Expanding Gas Power Transformation (EGPT), a new approach to the problem is introduced and described. Its scope for application in gas transmission and distribution operations worldwide is discussed. The energy effectiveness, CO_2 reduction and cost effectiveness of EGPT is explored.

2. GAS DEPRESSURISATION AS AN ENERGY RESOURCE

Gas expansion energy is available in any situation in which gas pressure is reduced as part of an ongoing process. The technical and economic feasibility of harvesting this energy will vary from site to site. Limiting factors for any technology will include the following:

- Insufficient or excessively variable gas flow
- Access to and availability of space at the pressure reduction site
- Unsuitable pressure drop
- Availability of an adequate connection to the electrical grid

Each technology will have its own particular advantages and drawbacks so that limiting factors will impact differently on each one. For this reason the estimate of the resource size is made without any attempt to exclude any plausible applications from the outset.

World consumption of natural gas for 2010 has been stated(1) as 3.17×10^{12} standard cubic metres (SCM). Most, if not all of this gas will have travelled via pipeline for at least part of its journey from upstream processing to the end user and will have undergone depressurisation several times enroute. An estimate of the worldwide potential for energy regeneration from this flow can be made only by introducing some assumptions. These are enumerated below.

a) All of the gas flow is transported by pipeline.

b) The gas undergoes pressure reduction in three stages: 120 to 65; 65 to 20 and 20 to 4 bar.

c) Pressure reductions below 4 bar are excluded from the resource estimation.

d) The gas enters each pressure reduction station at 10ºC and leaves at 4ºC.

e) The gas being transported is assumed to be pure methane.

From standard tables of thermodynamic properties(2) the mechanical energy available from isentropic expansion of gas flow through the assumed three pressure reduction stages is calculated as approximately 550kJ/kg. This quantity represents only about 1% of the heat of combustion and may seem insignificant. However, when applied to worldwide gas consumption, the ultimate resource size is equivalent to approximately 37GW at average 2010 consumption.

The above figure must be adjusted for a number of factors to reduce it to what might be called the recoverable resource. The first is the expansion-to-electricity conversion efficiency Applying a typical aggregate equipment efficiency factor reduces the recoverable resource to about 27GW under the conditions stated above.

The subsequent adjustment factors are much more difficult to estimate with any degree of confidence. Included among them are:

- Non-pipeline gas transport (LNG and other)
- Pressure reduction stations in unsuitable locations (climate, geography or surroundings)
- Actual pipeline gas composition

In the absence of the very detailed information required to quantify the above factors, a large but arbitrary derating factor of 80% is applied to arrive at a plausible and possibly even a conservative estimate of the realisable gas expansion electrical energy resource. The figures are summarised in the following table.

2010 Global Natural Gas Consumption	(SCM)	3.17×10^{12}
Assumed Pressure reduction steps	(bar)	120→65; 65→20; 20→4
Assumed entering and leaving gas temperatures	(ºC)	+10; +4
Power-productive enthalpy change after preheating	(kJ/kg)	550
Theoretical gas expansion power	(GW)	37
Maximum achievable electrical power	(GW_e)	26
Estimated realisable electrical power	(GW_e)	5.1

Table 1: Estimate of worldwide gas expansion energy resource using pre-expansion heating

If the typical developable pressure reduction site has a gas expansion power resource of 1.5MW, this would indicate a market for some 4,800 installations worldwide.

3. THE THERMAL BARRIER

Motive energy extracted from gas pressure reduction operations gives rise to additional cooling over and above the J-T cooling. This cooling must be counteracted so that the gas leaving the station is at a temperature suitable for pipeline transmission. In general, a temperature a few degrees above 0ºC is considered safe. A value of +4ºC has been used in the preceding section. This mandatory addition of heat is what is meant by the thermal barrier.

Heat can be added either before the gas expansion (preheating) or after the gas expansion (post-heating). Preheating has been almost universally adopted not because it is more efficient (it is actually less energy efficient) but because it avoids a number of complicating and possibly undesirable consequences, principally condensate formation and chilling of equipment. Countermeasures needed to implement a post-heating solution may include multi-step pressure reduction, insulation of pipework and equipment, but most of all a condensation inhibitor dosing and recovery system.

3.1 Temperature aspects

By way of example, the temperatures involved in various ways of accomplishing the mid-range (65→20 bar) gas pressure reduction step are illustrated in the enthalpy-pressure chart in Figure 1, following . A turboexpander efficiency of 85% is assumed in establishing the preheating and post-heating temperatures in this illustration.

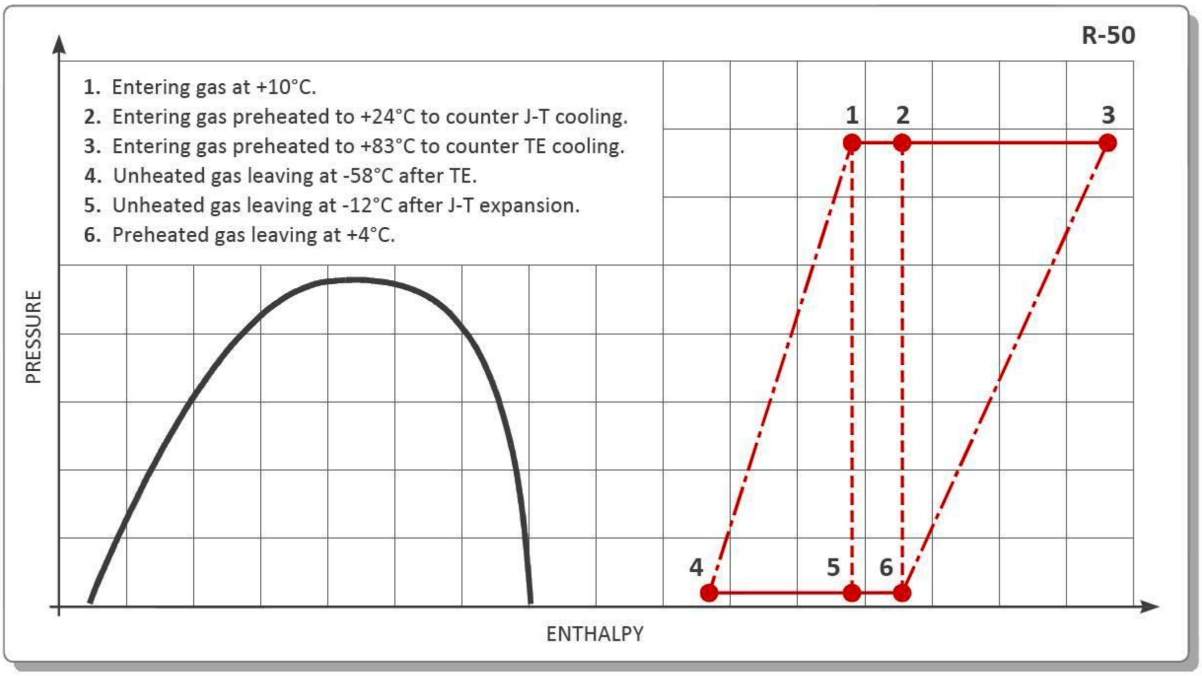

Figure 1: P-h sketch of 65→20 bar gas pressure reduction processes

1→2→6: Preheating followed by throttling expansion (dashed line)

1→5→6: Throttling expansion followed by post-heating

1→3→6: Preheating followed by turboexpansion (dot-dashed line)

1→4→6: Turboexpansion followed by post-heating

The first two sequences take place at constant enthalpy and involve no extraction of mechanical work. Post-heating would drop the gas temperature to -12ºC before the heating is applied. The preheating sequence is almost universally preferred to avoid this problem.

The third sequence involves a much larger input of heat in order to maintain the leaving gas temperature at the desired value after turboexpansion. The final sequence shows the very intense chilling of the gas when turboexpanded in a single step without preheat. Temperatures this low would be virtually certain to cause condensation unless the gas being transported was extremely pure methane.

Another difference between preheating and post-heating pressure reduction processes is in their motive energy yields. In this example the preheating process produces about 50% more motive power than the post-heating process.

3.2 Energy aspects

The theoretical resource for motive energy generation from the entire three-step pressure reduction process was given in the previous section as 550kJ/kg. The necessary thermal energy input consists of an equal amount plus an additional 85kJ/kg of Joule-Thomson cooling.

When these figures are refined to account for realistically achievable equipment efficiencies, the derating factors impact more on the electrical output than on the thermal input energy. The table below shows electrical energy yields and thermal energy inputs for pressure reduction processes using preheating for energy regeneration at +10ºC entering and +4ºC leaving temperatures..

Conditions	**Theoretical maximum efficiency**	**Achievable efficiency**
J-T heating input	85kJ/kg	85kJ/kg
TE preheating input	550kJ/kg	480kJ/kg
Total preheating input	635kJ/kg	565kJ/kg
Electrical output	550kJ/kg	385kJ/kg
Thermal input/Electrical output	1.15	1.47

Table 2: Unit energy quantities for electrical power production from gas pressure reduction

The obvious point to be made here is that any approach to exploit gas expansion energy for motive power production must include a provision for dealing with the very substantial input of heat needed to permit its operation on a natural gas pipeline.

4. OVERVIEW OF CURRENT APPROACHES TO EFFICIENT GAS EXPANSION

The task of reducing energy waste at pressure reduction stations has been addressed by a number of approaches. Many of these initiatives date from the late 1970's when the threat of fossil fuel shortages drew attention to the importance of efficiency. Four broad types of approach to the problem are described below to summarise the large number of individual schemes which have been proposed.

4.1 Existing equipment efficiency upgrades

Legacy equipment for gas heating at pressure reduction stations often included water bath-type heater units. These simple and straightforward assemblies provided an inexpensive and generally trouble-free solution to the problem of J-T cooling at pressure reduction stations. Replacement of this type of equipment with condensing boilers, more sensitive controls and compact shell&tube heat exchangers has produced major savings in gas consumption at PR stations. Upgrades of this type have generally been undertaken without any provision to explore motive power generation from gas expansion power.

4.2 Expansion turbine power generation using available waste heat

The potential for power generation using turboexpanders at pressure reduction stations and the the importance of the associated thermal barrier to were first clearly identified by Poživil(3) in 2004. The most direct way to deal with the thermal barrier to gas expansion power generation is to identify an accessible, adequate and steady source of waste heat at the appropriate temperature to provide gas heating. If this is possible, the gas expansion energy can be exploited without the need to cater for gas heating by any additional fuel consumption. In practice, the availability of waste heat suitable to enable gas expansion power generation will be limited to only a very small number of sites.

Recently attention has been called to the possible use of conventional gas combustion preheating in conjunction with gas expansion power production(4). The point being made is that power production by this technique is more efficient than gas-fired combined cycle power plants. From Table 2 one can see that electrical yields up to almost 70% could be achieved by this technique. The method would result in the gas consumption on the site being increased severalfold. If the price of electricity is substantially higher than that of gas(5) it can be economically attractive.

4.3 Post-heating and use of ambient energy gas reheat

Elements of this approach have been discussed in the preceding sections. This approach allows the use of ambient heat to provide most of the gas warming and does not involve fuel combustion(6).

The principal drawback of this approach is the necessity to take measures to inhibit the formation of condensate in the chilled gas. These include the likely need to use two-stage pressure reduction and the installation of metered chemical dosing equipment. The lower power yield and the need for consumables also constitute a challenge to the technology.

4.4 On-site auxiliary power generation equipment

This approach involves a direct assault on the thermal barrier by deliberately providing on-site powergen as a source of waste heat whose size can be tailored to provide the heat input needed to liberate the gas expansion energy(7). This approach to gas heating generally uses preheating. The equipment used to provide the auxiliary powergen can be diesel engine, fuel cell or any type of prime mover capable of using the type of fuel being used at the site. Here also, the need for auxiliary powergen equipment and additional consumables on the site will feature in the feasibility assessment wherever this approach is being considered. The environmental benefits depend on the type of fuel used.

5. THE EXPANDING GAS POWER TRANSFORMATION PROCESS

The EGPT process makes use of a very straightforward but technically novel method to deal with the thermal barrier. The method involves no combustion of any fuel whatsoever in the production of power from gas expansion. The key to the EGPT process is its ability to transform part of the power generated by gas expansion into heat via a transcritical heat pump. The process is fully documented in patents pending(8).

This type of heat pump is uniquely able to deliver heat at high efficiency to cold incoming pipeline gas and raise its temperature to the high levels above 80ºC needed to counteract high efficiency turboexpansion. The transcritical heat pump is able to accomplish this task while using only a fraction of the power produced from gas expansion. The long continuous heat rejection temperature ramp needed for effective heat transfer is a natural consequence of rejecting heat at pressures above the critical point of the refrigerant. Using this recipe, the motive power produced by gas expansion is adequate to satisfy fully the very stringent thermal barrier requirements whilst also supplying a significant portion of this totally carbon-free power for export or other productive use.

Transcritical heat pumps are commercially available in modules with thermal power outputs from 50kW to more than 1MW. Hydrocarbon turboexpanders are available for application over the full range of gas transmission pressures and in rated power from 150kW up to about 15MW. This size range will allow the EGPT technique to be applied to the vast majority of natural gas pressure reduction sites using standard production components.

5.1 Heat production by subcritical and transcritical heat pumps

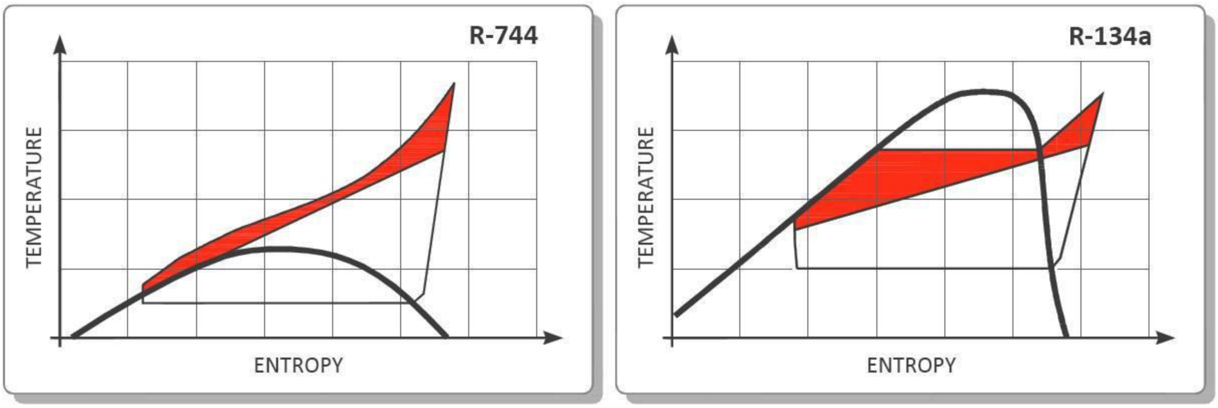

Figure 2: Heat rejection temperature profiles in subcritical and transcritical processes

The figure above illustrates the difference between conventional (subcritical) heat rejection from a heat pump and the corresponding process in a transcritical heat pump. The right part of the sketch illustrates the heat rejection process in a subcritical reverse Rankine cycle. The upper trace indicates the gas temperature profile, descending towards the left. First comes a rapid temperature drop during gas phase desuperheating, followed by condensation at constant temperature, followed by liquid phase subcooling. The straight line rising toward the right shows the rising temperature of the medium being heated. The shaded area between the two traces is a measure of the irreversibility or exergy loss in the process. Given the jagged nature of the three-part gas cooling trace, it is clear that a close fit between the two temperature profiles is not possible over the whole of the heat transfer process.

The left-hand part of the figure shows the corresponding heat rejection process when the gas cooling process takes place in the supercritical regime. It is intuitively clear that the two temperature traces can be brought much closer together in the supercritical regime. In fact the supercritical isobars become progressively straighter as the pressure is increased. Hence the exergy loss can be reduced as the heat rejection pressure is increased. The other favourable factor is that the working pressures and temperatures of the cycle are no longer limited by the critical point as they are in subcritical cycles.

A comparative performance study(9) of the best subcritical heat pump cycles and the CO_2 transcritical heat pump cycle for producing sanitary hot water at 70ºC has shown very clearly the superiority of the latter. Coefficient of performance (COP) figures for a transcritical heat pump in this application were shown to be about 25% higher than those of the very best subcritical equipment. In addition the temperature capability of commercially available transcritical heat pumps extends up to 90ºC, a temperature often needed to counteract high-efficiency turboexpansion chilling. Additional benefits of using CO_2 as the heat pump working fluid are its exceptional safety and stability and its very low GWP (Global Warming Potential).

5.2 EGPT system performance

The technical and practical viability of the EGPT process is critically dependent on the efficiency of the heat pump. As shown in preceding sections, the generation of one unit of gas expansion power requires an input of about 1.5 units of thermal power. Hence the heating COP of the heat pump must be substantially greater than 1.5 in order to produce any surplus of exportable electrical power. The value of the COP achieved will depend on the temperature at which ambient energy can be accessed and the gas preheating temperature required. Commercially available transcritical heat pumps can achieve COP values of 3.2 to 4.6 while supplying gas heating at 85ºC, depending on the ambient resource temperature. The table below shows the calculated performance of an EGPT installation on a small PR station handling typical North Sea natural gas.

Ambient reservoir temp (ºC)	**0**	**10**	**20**	**30**
Gas preheat (kW)	1360	1360	1360	1360
Heat pump motive input (ºC)	425	370	325	295
Heat pump peripherals input (kW)	45	40	35	35
Existing site electrical load (kW)	10	10	10	10
Total on-site electrical load (kW)	480	420	370	330
Expander-generator electrical output (kW)	865	865	865	865
Exportable electrical output (kW)	385	445	495	535

Table 3: Calculated performance of 65→20 bar EGPT system handling 30,000 SCM/hr

The ambient temperature threshold for technical viability of the process would appear to lie slightly above 0ºC where the exportable electrical power is in the region of 50%. This however is not the sole deciding criterion for evaluating the process, since the application of EGPT has also eliminated completely the need for gas heating and electrical power import onto the site.

5.3 Zero-export EGPT applications

In the majority of possible applications an adequate connection to the electrical power grid would be required. However, some pressure reduction stations are located at a considerable distance from any grid power, or may have only a very small capacity supply. Such installations may be candidates for zero-export EGPT systems if the gas flow is substantial and particularly if they operate at high pressures where J-T heating gas consumption may be considerable.

Economically viable EGPT solutions are possible in this type of situation by sizing the turboexpander and the heat pump with the sole purpose of catering for the site gas heating thermal load and electrical load. Using this design approach it is possible to reduce the sizes of both the turboexpander-generator and the heat pump by more than 50%. Only part of the station flow is turbo-expanded. The remaining part of the station flow, expanded by throttling, has a much lower specific reheating demand. This results in a considerably smaller heat pump. The effect is then to reduce both the energy waste and the total CO_2 emissions from the site to zero. Provided the operating pressure regime is favourable and the gas flow is adequate, a financially and environmentally attractive EGPT application may result even without power export.

6. ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

It is difficult to produce any universally applicable recipe for calculating the economic attractiveness of the EGPT technology. One reason is that the relative prices of electricity and gas vary widely from country to country. In addition an increasing number of countries are introducing incentives for environmentally desirable developments. These include feed-in tariffs for renewably generated power and in some cases an incentive based on CO_2 emission reductions.

Another source of variability is the ambient energy collector, an intrinsically site-specific part of every installation. Other site-specific particulars are: the entering and leaving gas pressures; the gas composition; the yearly and daily gas flow pattern; the local climate and geography; the electrical grid connection; etc.

Acknowledging all of the above limitations, preliminary investigations made into installations from $0.7MW_e$ to $3.0MW_e$ have indicated EGPT nominal payback periods ranging from 3 to 7 years depending on gas cost and electricity feed-in tariff details. Even shorter payback times are possible if a monetary value can be assigned to CO_2 savings. Investigations have included air source, well-water source and seawater source designs. Also, the power produced from the EGPT process is clearly carbon-free since no fuel whatsoever is consumed in its production.

A comparison with an established renewable energy technology is instructive in providing a benchmark for cost-effectiveness and CO_2 effectiveness. The table below gives an indication of how the estimated EGPT primary performance measures compare with the well-established figures for onshore wind power(10).

Technology	**Onshore Wind Power**	**EGPT Pressure Reduction**
Yearly Duty Factor	0.3	0.8
Installed Cost (€ / Rated kW_e)	1,200	2,500
CO_2 Savings (Tonne / yr / Rated kW_e)	1.5	2.5

Table 4. Estimated installed cost and $C0_2$ effectiveness figures vs onshore wind power

The figures of merit for the EGPT process are a result of several factors. The anticipated high duty factor results from the fact that the resource is part of the gas delivery chain. Moreover, gas flows in a network can often be apportioned to reduce flow variations in selected PR stations. This can give a much higher duty factor than a technology which depends directly on a fluctuating natural phenomenon such as wind.

The CO_2 effectiveness of the EGPT process arises from two separate benefits: the emissions from conventionally-produced electricity displaced by the exported green electricity and the gas consumption avoided in counteracting the J-T cooling effect.

The EGPT combination of simplicity, wide applicability, favourable economics and exceptional environmental effectiveness offers the industry an exciting new tool for improving efficiency and generating authentic green power in natural gas transmission and distribution.

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