OPORTUNITIES OF WASTE HEAT RECOVERY AT NATURAL GAS TRANSMISSION SYSTEMS

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Background

The dependence of Europe on foreign sources of primary energy and the growing demand for electricity are the main driving forces behind utilizing non-traditional, secondary energy sources, to which secondary waste heat belongs. Compressor stations installed on transmission have huge potential for waste heat recovery, increase efficiency of operation and thus reduction of overall environmental footprint of transmission systems.

Currently there is only limited number of installations of waste heat recovery systems in the world providing heat for 3rd parties (e.g. green houses), compressor work in steam turbine driven of compressors and production of electricity. Main reason is that transmission systems are operated in very volatile way and this makes waste heat recovery systems hardly economically viable.

To utilize waste recovery potential it is necessary to asses many factors: transmission system operation, gas turbines fleet availability, their operational modes, waste heat recovery technologies (ORC, Steam Cycle), kind of produced energy (mechanical work/electricity); energy market situation, regulation aspects and others. This is not an easy task because there are not much literature and other source of information available.

For Eustream the driver to launch the waste heat recovery analysis was a fact that in spite of relatively high thermal efficiency of installed gas turbines still more than 60% of the energy supplied by fuel is unused as waste heat of high temperature potential at temperature level of 450 – 500°C.

Aim

To describe the philosophy and methodology of how it is possible to utilize waste heat at compressor stations taking into account their specific conditions.

To explain how this philosophy and methodology was used in the transmission system of Eustream – the Slovak Transmission System Operator (75% of Russian natural gas deliveries to EU).

To describe a project of Waste Heat Recovery at Compressor Station 01 Veľké Kapušany (the biggest CS in the European Union) - the VOTE project.

Methods

To make possible to consider possibilities of waste heat use at the transmission system, it is necessary to make a series of analyses and comparisons, which represent a compact general methodology. Major questions relate to the way of utilizing waste heat and used technology:

- to use energy for driving a compressor unit for natural gas transport
- to use energy for electricity production
  - classical steam system
  - ORC system (Organic Rankin cycle)

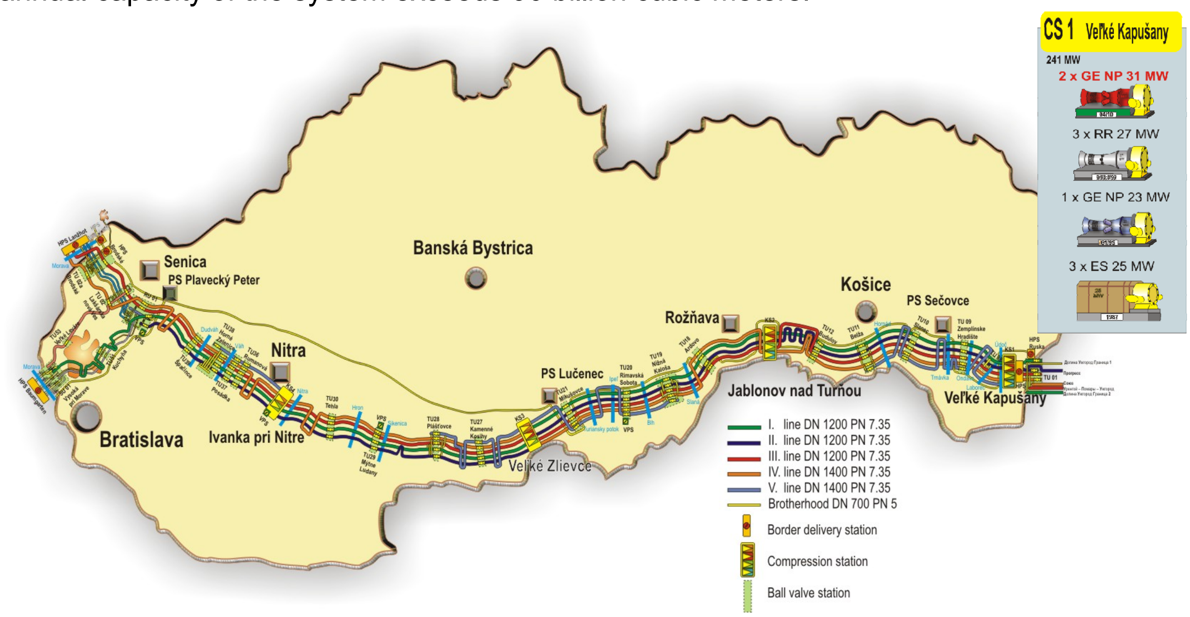
At each stage of methodology a real example is provided based on Waste Heat Recovery at CS01 project (VOTE).
Stages of assessment:

To identify compressor stations and gas turbines suitable for waste heat recovery mainly the following criteria were taken into account:

- Natural gas transmission through compressor station (CS) and operations of CS in a year
- physical & chemical composition and temperature of gas
- pressure conditions during transmission
- characteristics of gas turbines
- dispatching system – priority of gas turbines operation (preferential use of machines with higher thermal efficiency), determination of the configuration of the compressor fleet for transmission
- Statistics of starts and shutdowns of machines (planned, unplanned emergency)

Within these criteria it is necessary to look for a compressor station with very high utilization in a year. It is ideal if this is a compressor station with non-stop operation. Such CS are usually located at the beginning of the hydraulic system (behind a Border Delivery Station), or at significant nodes of the transmission network.
Thereafter it has to be analysed machine fleet at the relevant compressor station and consider their percentage annual use. The most suitable machines are, of course, those of the highest usage or highest priority of putting into operation. Usually these are turbines of the highest total efficiency or with high flexibility of operating. At utilizing waste heat from several machines it has to be taken into account also their mutual distance. Closeness of machines is an advantage at designing an engineering solution.

VOTE Example:
The Slovak transmission system consists of four to five parallel pipelines, mostly 1200/1400 mm in diameter with an operating pressure of 73 bars. The pressure differential needed for continuous gas flow is ensured by four large compressor stations with an aggregate power of more than 1000 MW. The most important station is located at Veľké Kapušany at the Ukrainian-Slovak border. With a total power of nearly 300 MW, it is the biggest compressor station in the EU, allowing an entry flow of almost 300 million cubic meters per day. The annual capacity of the system exceeds 90 billion cubic meters.



Based on the above-mentioned criteria it was decided that the most suitable CS for using waste heat potential within the transmission system of eustream, a.s. is the compressor station in Veľké Kapušany and this mainly due to non-stop operation. As the most suitable machines for waste heat utilization appeared 2x GE PGT 25+ DLE (31MW) and 3x Rolls Royce RB211 (27MW), because they have the highest priority of putting into operation, the machines are located in a row in close vicinity.

To identify number of gas turbines to be included in a waste heat recovery project:

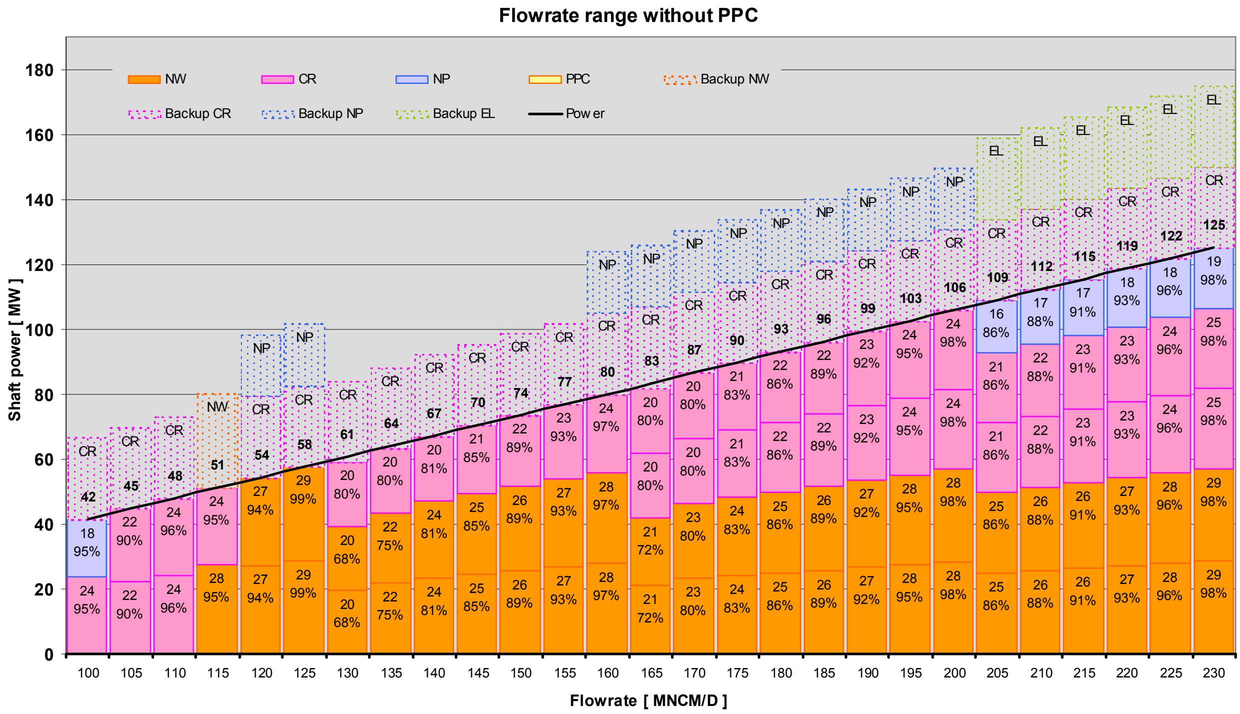
- statistics of gas turbines operation (annual number of fired hours)
- load diagram of CS and gas turbines
- forecast of transmission flows
- Statistics of machine availability
- Reliability of operating

For determination of the final count of machines, which have to be included to the system of waste heat utilization it is necessary to define margin conditions:

- Minimum count of machines in operation and their minimum load
- Maximum count of machines in operation and their maximum load

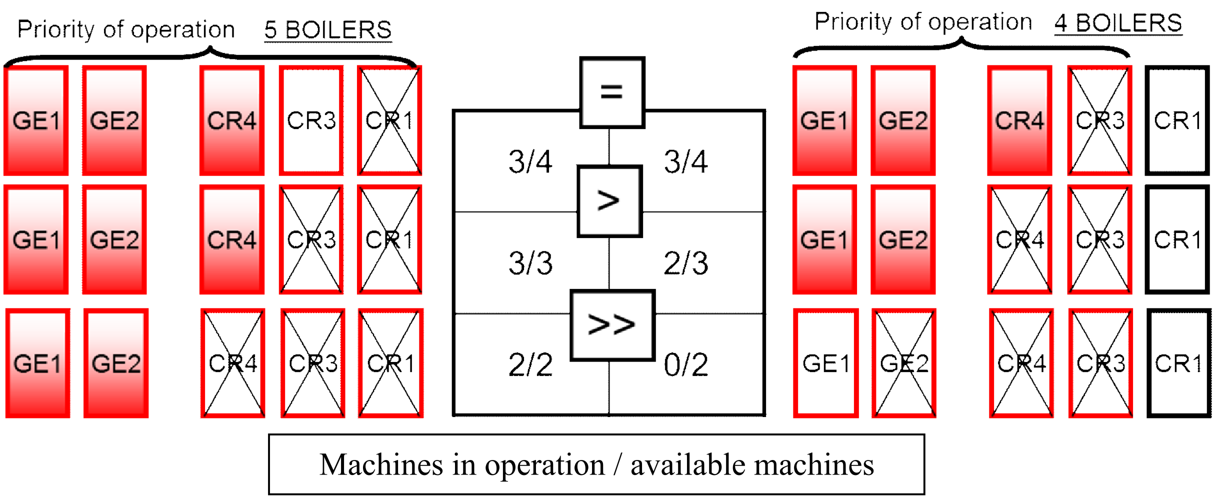
Within these limits it is moreover necessary to determine the count of machines for active utilization of waste heat and count of standby machines. The most important criteria are economic return (more active machines = higher revenues) and operation reliability – the maximum has to be reduced by probability of machine shutdown due to failure.

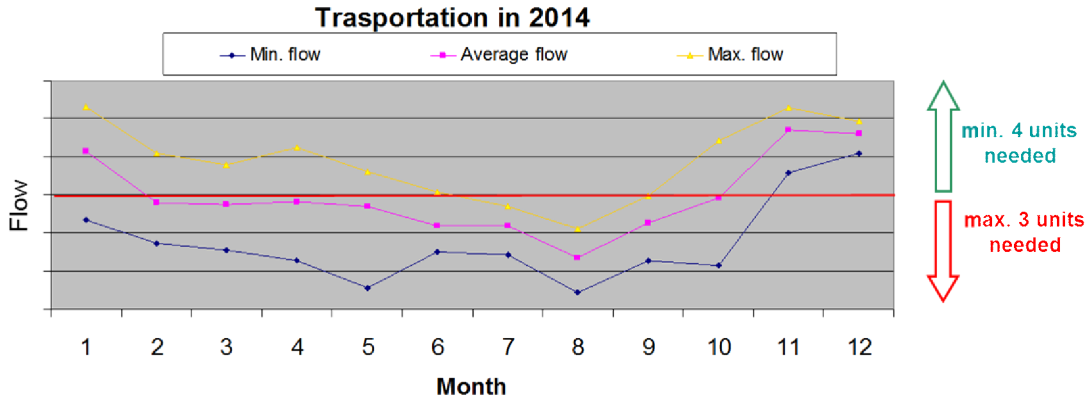
VOTE example:
Based on analysis of machine need depending on flow, were as minimum determined two machines working at 70% of power. Maximum four machines are in operation + one as standby.



Graph 1: Machines necessary for operation for certain flow

For determination of optimal count of active turbines the statistics of machine failures was used (there were cases when three machines were in failure at the same time) and analysis of expected flows.





After taking into account above mentioned criteria and analyses it showed as the most suitable solution usage of five gas combustion turbines equipped with five waste heat boilers. Whereas always only two or three waste heat boilers will be in operation. Other two boilers will serve as standby in case of replacement of gas combustion turbines in operation or their unexpected outage.

<u>To analyze existing infrastructure available:</u>

In view of considering capital demandingness availability of the following networks appears to be a big advantage:

- electricity grid – voltage level, capacity
- water availability for industrial purposes (for steam production, cooling, …)
- sewerage system, drainage
- industrial structure with high heat consumption (greenhouses, boiler house, factory, …)

VOTE example:
As a big advantage for the project showed the availability of 110kV distribution system, which will enable leading out of electric power from generator through the existing substation 110kV and which is at the present time used for power supply of compressors with electric drive. Simple extension of the existing substation will enable provision of high flexibility of power leading out in the same way as an option of isolated-network operation in the event of supplying own consumption of the compressor station. This flexibility will bring saving of operating costs of the compressor station in view of saving distribution fees in isolated-network mode (by direct supply of CS and compressors with electric drive).

In view of availability of water resources (lack of surface water – river, however sufficient underground water) as the most suitable solution for cooling emission steam appeared cooling through air condenser.

Proposal of basic variants for utilizing waste heat:

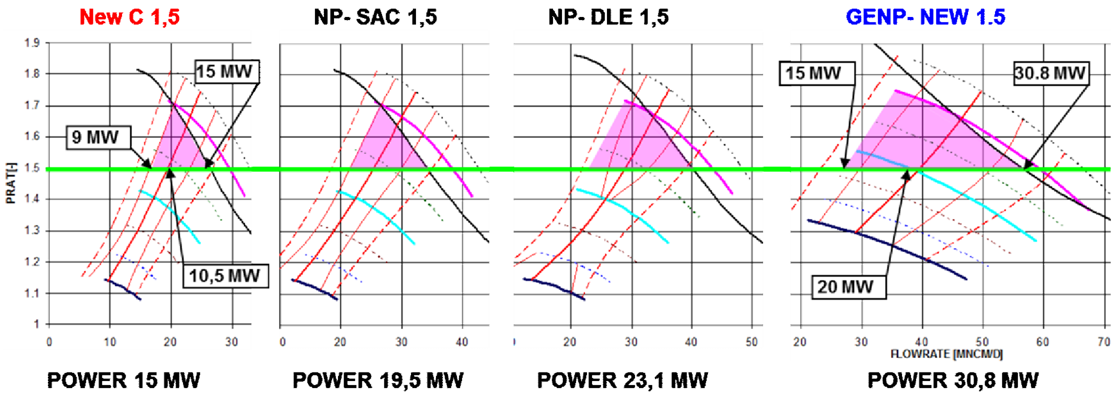
There are two basic possibilities at CS of utilization of waste heat:

- mechanical work production to drive gas compressor
    - analysis of impacts to CS operation – change in dispatching system, time demand of cool/warm start, impact of emergency shutdown, analysis of parallel operation of existing fleet + new gas compressor
- electrical power production
    - analysis of requirements for stability of output power

Compressor drive looks at first sight as a logical choice for operators of transmission systems (this is the core business). However it is necessary to realize risks connected with creating a very strong feedback in closed cycle, control mechanism of which will be much more complicated in view of operation compared with the standard system. Dispatcher control will be much more demanding. Flexibility of operating can be reduced due to limitations in parallel operation of existing compressors and the new compressor, mainly if there are significant power differences among them. Moreover under certain circumstances there is a risk of so called domino effect. Failure of gas turbine, flue gases of which are used in waste heat system, will cause outage of mechanically driven compressor due to lack of power and shift of its working point into the zone of surge. This problem can be solved by immediate drop of compression ration of the entire station; this solution is supported also by the fact that after failure of some machine, pressure drop at CS output occurs.
Another risk in view of operation optimisation in the event of compression work production there is a need to obstruct a part of heat in bypass chimneys, because power obtained for compressor drive with steam drive can be redundant.
On the opposite, electric power production works in open system without direct effect to natural gas transmission and completely uses enthalpy contained in flue gases for transformation to higher energy form. High demands to stability of supplied power are usually a disadvantage.

VOTE example:
In case of CS01 analysis of parallel co-operation showed serious limitations of parallel co-operation of compressors meaning complicated dispatcher control of transmission and high risk of domino effect. Main reason of the domino effect is linkage of compressor power driven by a steam turbine for operation of compressor units, from which flue gases are used for steam turbine operation (Picture 1). In the event of failure of one of these machines at the same time drop of steam turbine power will occur by approximately 4.5 MW. This will immediately shift the operating point of the compressor driven by steam turbine at given compression ratio from the position for 15MW to power line of 10.5 MW. Because at power of 10.5 MW the operating point is located at compressor pumping, risk of failure of also this compressor is threatening at significant dynamic changes. Due to this reason for utilization of waste heat for production of mechanical work compressor is needed with wide extent of operating zone.

In the same way, the market analysis showed that at using flue gases from three combustion turbines, for wide regulation extent at steam turbine coupling, there is no available suitable compressor for natural gas transmission in the market for given power, which would include the entire scope of necessary compression ratios. With respect to the fact that the goal of Eustream is, first of all, to provide for safe and reliable gas transmission, the final solution was directed to utilization of waste heat for production of electric power, interaction of which with gas transmission will be minimal.



New C	POWER [MW]	FLOWRATE [MNCM/D]
MAX	15	26,5
MIN	10,5	19,5
LEFT	9	17

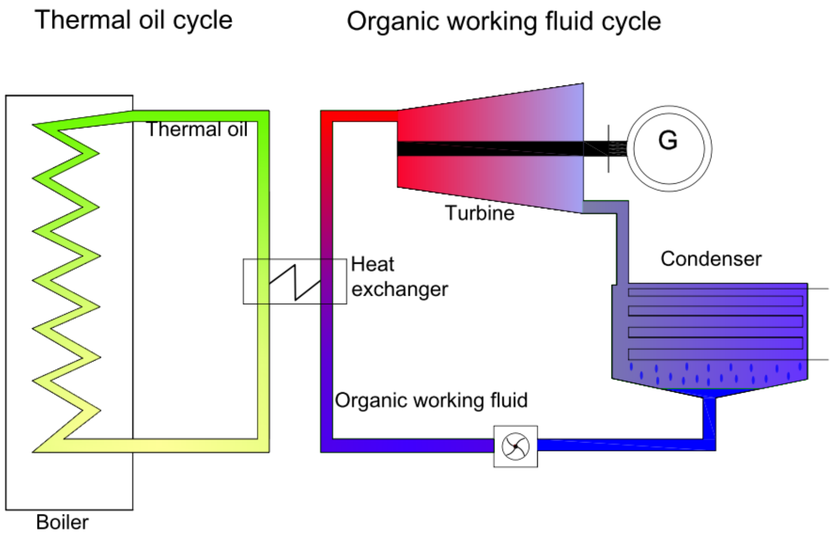
GENP	POWER [MW]	FLOWRATE [MNCM/D]
MAX	30.8	57
MIN	20	38.5
LEFT	15	27.5

Picture 1: Parallel operation of compressors

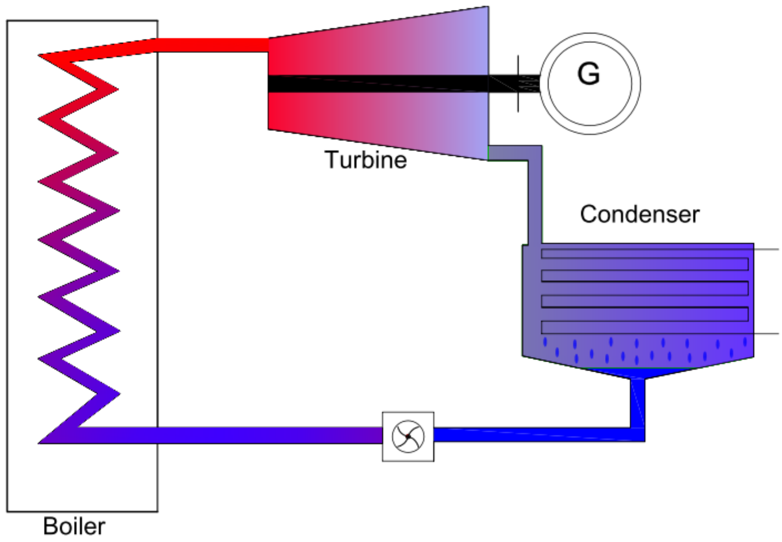
Analysis of possible technical solutions:

At the moment there are two possible technologies enabling waste heat utilization, which have their advantages and disadvantages:

- heat transferred to thermal oil and then to organic medium, Organic – Rankine Cycle (ORC) – lower Capex, lower efficiency, ideal for low temperature heat, applications at sites with limited availability of water
- heat transferred to steam, classical Clausius-Rankine Cycle – high flexibility in sizing, high efficiency, proven technology



Organic - Rankine Cycle (ORC) - uses organic substances



Clausius - Rankine Cycle – uses water

Organic - Rankine Cycle (ORC) brings compared with the steam cycle certain advantages, for example lower capital cost and lower pressures in distribution systems of heat transferring and working media. Thermodynamic efficiency of ORC cycle is however lower than at steam cycles with high-pressure admission steam.
Most of installation of technology with ORC cycle in the world represents unit electric power by orders around hundreds of kW up to several MW. ORC cycle can be used to advantage, first of all, in applications, where is preparation of high-temperature admission steam problematic in terms of technology, or in applications with a possibility to use thermal power by orders of units or dozens of MW, where the steam cycle installation is not profitable due to high capital costs. Therefore are these technologies mostly connected with electric power generation, for example from energy released at combusting biomass, or at using energy from various media of temperatures approximately **300 °C**. In case of waste heat from GT the temperature of flue gases at the level of even up to 450 to 500 °C.
As we already mentioned ORC technology is though less demanding in terms of capital, however its efficiency is in the given application in comparison with classic steam cycle lower and with respect to nature of heat transferring media (liquid) requires higher consumption of electric power.
Moreover, ORC technology introduces in safety of CS operation improper element in a form of inflammable organic substances.

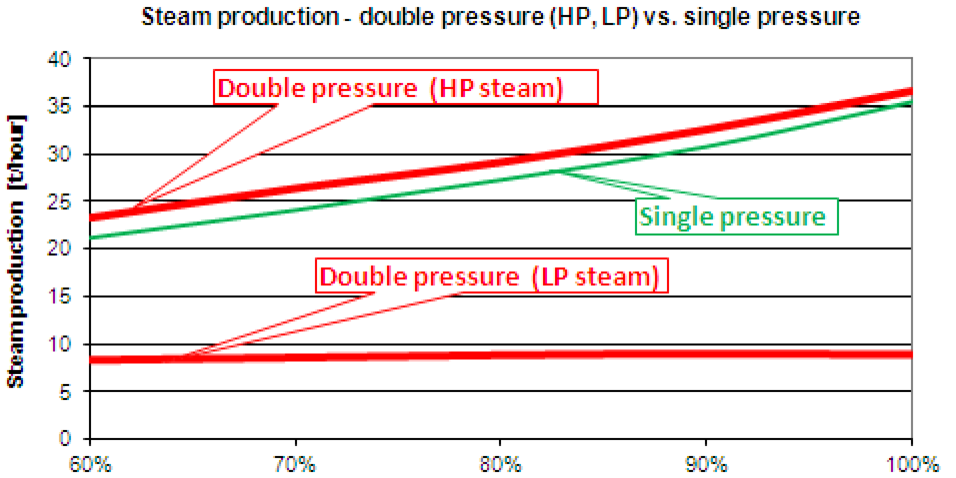
On the other hand, Clausius-Rankine Cycle is widely used and tested technology with high flexibility of sizing and higher efficiency than ORC. Higher capital costs compared with ORC can be eliminated, if there is more waste heat boilers connected to one bigger steam turbine. This is, so far, not enabled by ORC technology at higher powers due to unavailability of appropriate expanders.
Within Clausius-Rankine Cycle also technical design of waste heat boiler has to be considered:

- single-pressure system - lower CAPEX, lower efficiency
- two-pressure system – technically more complicated solution, higher CAPEX, higher efficiency

VOTE example:
Results of efficiency analyses and capital demandingness led to using the Classical Clausius-Rankine Cycle with technology of two-pressure steam system:

Comparison of electric efficiency of two-pressure steam system and ORC cycle

	Ambient temperature	Power load of turbines	Flue gases amount	Flue gases temperature	Heat amount in flue gases	Electric power at terminals	Gross electric efficiency	Parasite consumption of electric power	Net electric efficiency
	°C	%	kg/s	°C	MWt	MWe	%	MWe	%
Steam cycle	15	80	237,3	490,4	117,21	25,39	21,66	0,762	21,01
ORC	15	80	237,3	490,4	117,21	21,04	17,95	2,244	16,04

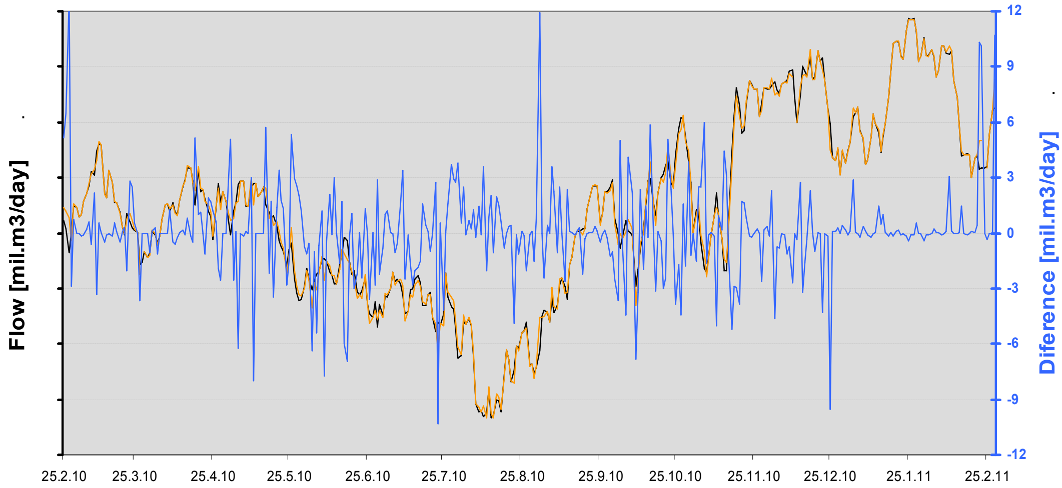


Mitigation of volatility of flow and thus energy produced:
Despite application of the system of waste heat utilization at CS still natural gas transmission remains the priority and therefore it is necessary to cope with impacts of high volatility of lows to production (mainly in the event of electric power generation). Both technical and commercial measures can be used.

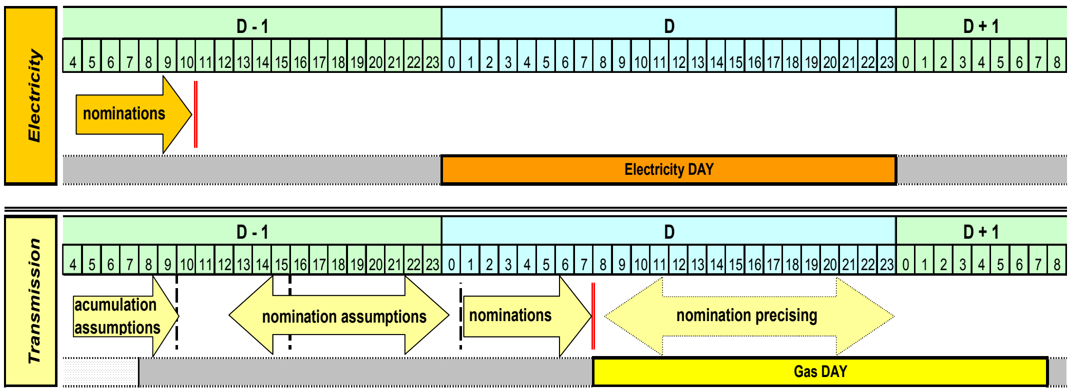
- Technical measures:
  - limit GT connected - output analyzed based on the minimal flow anticipation
  - supplementary heating (additional burner in a boiler) - electric output stabilization
  - possibility of optimisation of machine running in view of dispatcher's control of machine putting into operation with respect to the amount of generated electric power

- Contractual measures:
  - Based load - fixed heat / electricity delivery (16MW)
  - the rest based on nominations Day -1:
    - differences settled based on deviation billing (positive/negative impact possible)
    - electricity supply differences borne by distributor (reflected in the electricity price)
    - difference covered by intra-day market

VOTE example:
After analysis of transmission volatility and comparison of nominations of gas and electric day we decided to use additional heating burners.



Deviation: nomination assumptions / real flow



Comparison of nominations: EE and Gas

Power of additional heating burners was optimised with respect to assumed flows and statistics of variances between the planned and real flow, so that it is able to cover potential variance between nomination and reality and at the same time fulfil strict emission limits required by relevant legislation. Assumed maximum heat power of additional heating equals to 30% of the total operated heat power of GT.

Economic and multi-criteria analysis (to find optimal balance between economical viability and technical criterions (usually difficult to evaluate))

Final decision of the most suitable technical and economic solution cannot be defined only on the basis of evaluation of elementary economic indicators, such as IRR, NPV, or paybacktime of invested capital resources. New technological unit implemented into organism of the compressor station will affect operation and reliability of the entire compressor station in a significant way. Therefore it is more suitable to use for comparison of particular alternatives multi-criterion evaluation, which includes economic, technological, as well as safety criteria.
The following criteria were selected for evaluation sorted from the most important ones to the least important ones:

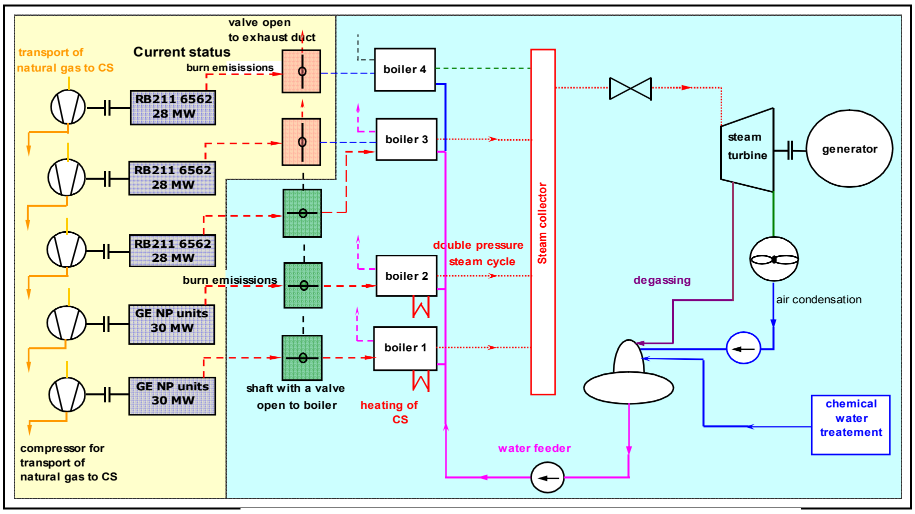
- Effect on transport reliability
  - Effect on operation of combustion turbines
  - Effect on operation of gas compressors
- Internal Return Rate
- Safety risks of installed equipment

- Duct systems
- Use of steam
- Use of thermo-oil

- Availability of installed equipment
  - Boilers
  - Expander related equipment
  - Duct systems
- Capital costs
- Demand for new premises

VOTE example:

The result of multi-criterion analysis was - Production of electricity using steam cycle in 4 boilers for 5 combustion turbines connected. Because of CAPEX optimization a special design of one of the boilers was used (see Picture 2 – boiler 3). This is a boiler power dimensioned to one gas turbine, but with two independent inputs. One turbine is then connected to the boiler directly and the second one through flue-gas dusting.



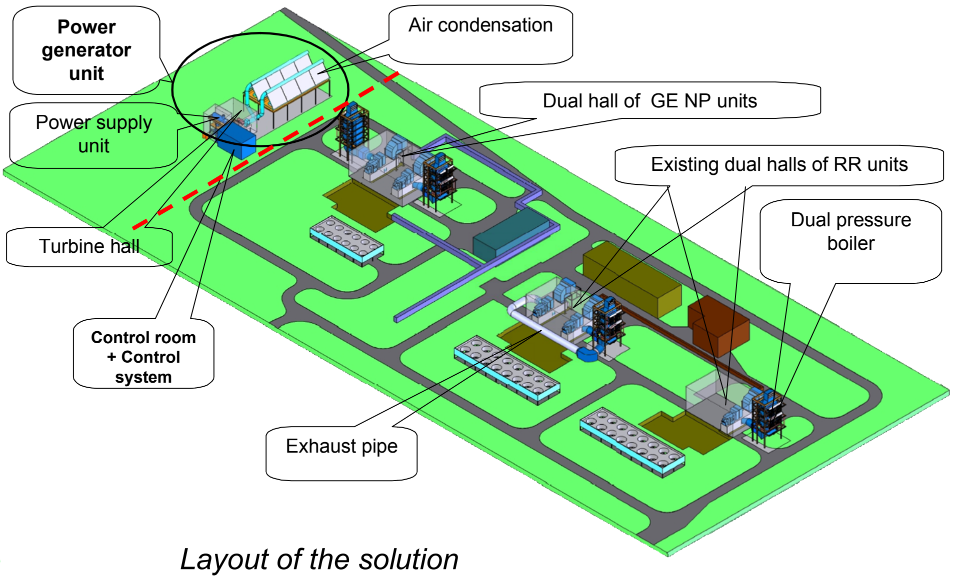
Picture 2: Diagram of the solution

Results

Result of the study is the philosophy and methodology of how it is possible to utilize waste heat at compressor stations taking into account their specific conditions. It can be used as general instructions for TSOs to consider their systems.

In order to use waste heat potential Eustream launched the VOTE project, which is currently being implemented at CS01 Veľké Kapušany compressor station. A goal of the project is to utilize the energy potential from the existing 5 gas turbines (3x Rolls Royce RB211 (27MW), 2x GE PGT 25+DLE (31MW)) - three (at least two) in continual operation is expected (two turbines in backup). Electricity will be produced using classical steam Clausius-Rankine Cycle with waste-heat boilers featuring double-pressure steam system including stabilization burners for additional heating.

By implementing the utilization of waste heat described in this contribution, the efficiency of gas combustion turbines will be increased from average 35% to almost 57% of the combined cycle. 200 GWh of electricity and 33 GWh of heat will be produced annually without any needs for external sources of primary energy (fossil fuel savings) and thus significantly reducing environmental footprint of CS operation. IRR of the project is more than 20%.



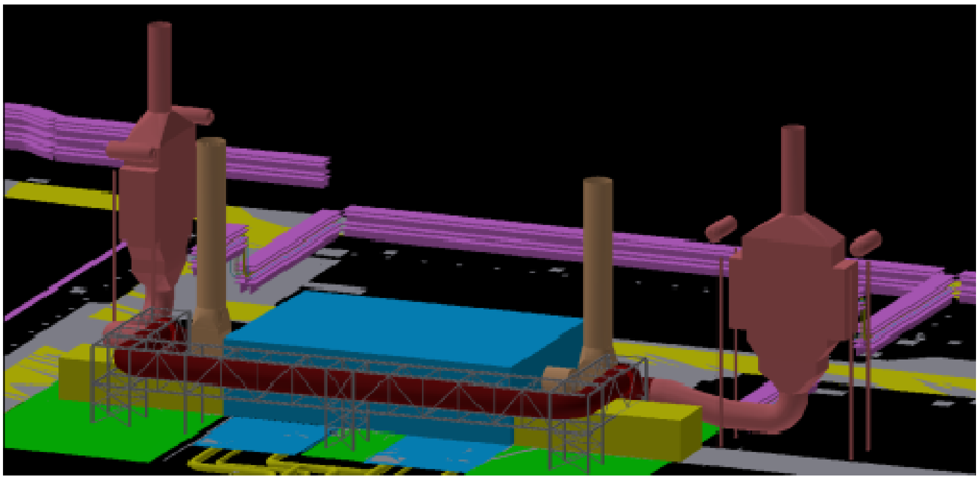
Layout of the solution

At the present time the project is in the phase of preparation of basic engineering, urban land permit, building permission, as well as preparation of tender documentation for selection of the Contractor. Results of basic engineering show minimum changes against the technical design analysed in advanced preparatory phase of the project.

Need of installation of additional heating in order to stabilise the output electric power was confirmed.

Technically and economically more appropriate showed the solution with installation of five boilers (instead of 4 boilers + flue-gas dusting) for waste heat for five gas turbines and this mainly due to the following reasons:

- Highly risky and costly installation of flue-gas dusting over the existing pipe yard (this solution is appropriate for green field installation)
- Installation over dangerous zones of explosion
- Deterioration of maintenance of GT pipe yard
- Higher pressure loss, higher losses of heating radiation to surrounding
- Installation of accessories: carrying structure, shutters, fans including the sealing air system
- OPEX – non-stop operation of fans of the sealing air system
- Limitation of service activities at the existing pipe yard.

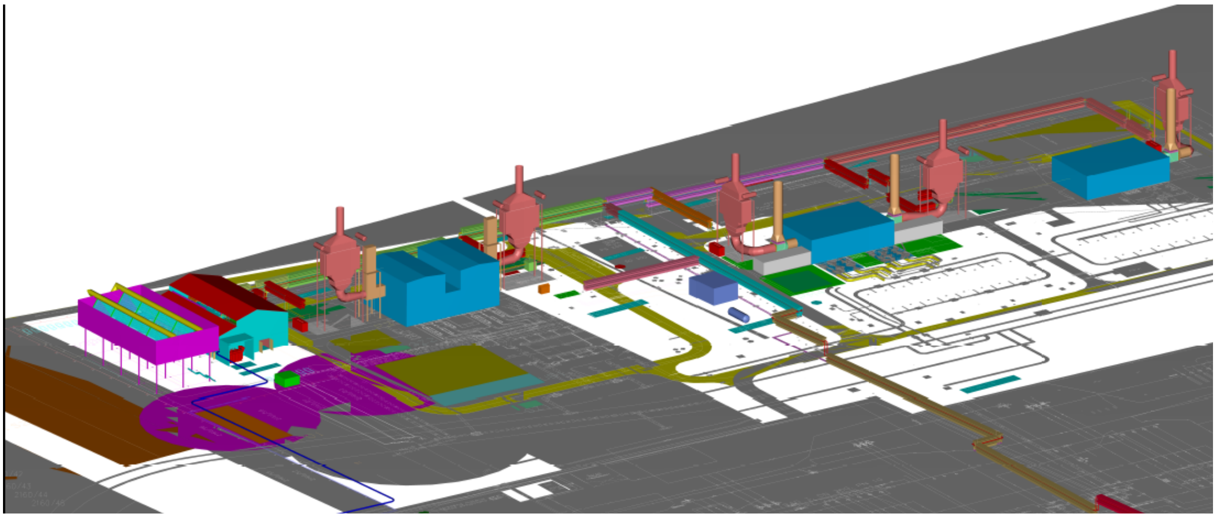


Alternative with connecting flue-gas dusting (diameter - 4m)

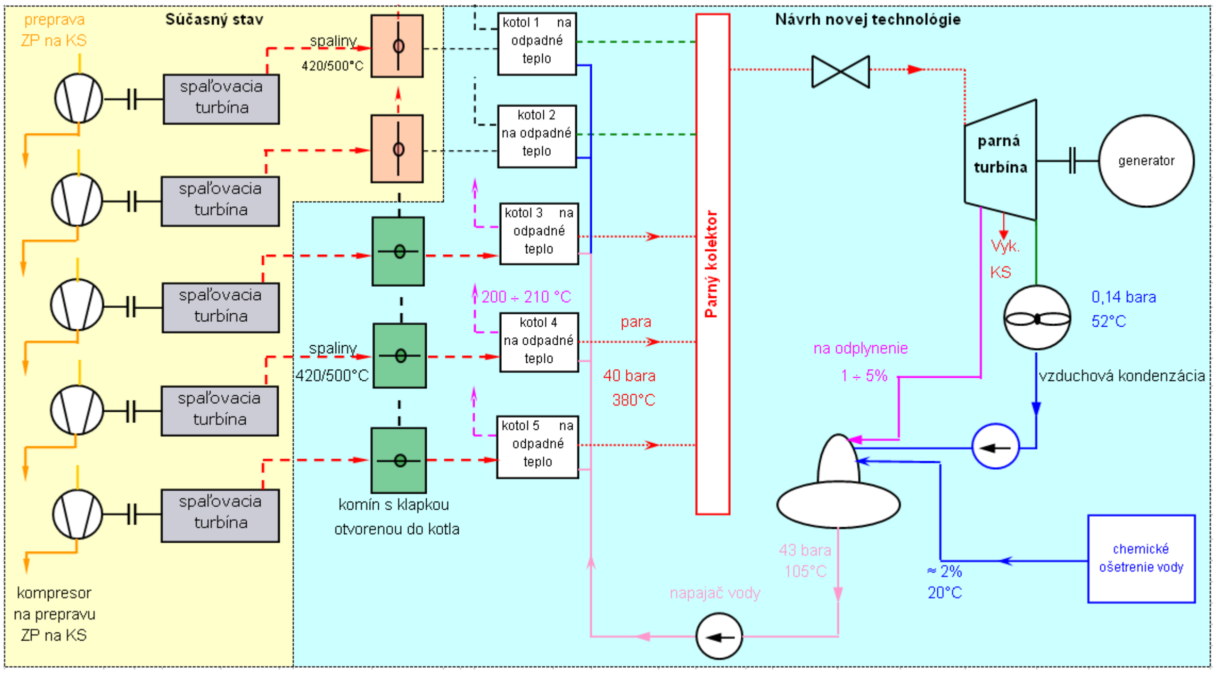
Installation of flue-gas dusting in the existing plant had in case of VOTE many safety risks and only minimal saving of capital costs. With respect to the below mentioned the installation of flue-gas dusting showed as disadvantageous, whereas the mentioned solution shows to the fact that assembling the flue-gas dusting is profitable only in case of the project, which would be implemented at green field installation.

The last change compared with the original solution is replacement of heat consumption from heat exchangers of boilers, by heat consumption from regulated consumption of steam turbine and this mainly due to the following reasons:

- Requirement for higher heat consumption from original 6MWt to 12MWt (besides CS heating also greenhouse heating)
- Independence of heat supply from boiler operation and combustion turbines assigned to them
- Higher average annual total efficiency of the unit
- Higher revenues from electric power sales during summer operation



3D model of the final solution



Simplified technological scheme

Summary / Conclusions

Compressor stations installed on transmission have huge potential for waste heat recovery, increase efficiency of operation and thus reduction of overall environmental footprint of transmission systems because they usually work in simple cycle due to high volatility of their operation.

To utilize waste recovery potential it is necessary to asses many factors: transmission system operation, gas turbines fleet available, their operational modes, waste heat recovery technologies (ORC, Steam Cycle), kind of produced energy (mechanical work/electricity); energy market situation, regulation aspects and others.

The paper contains detailed description of methodological procedures for designing a waste heat recovery solution - it can be used as general instructions for TSOs to assess opportunities at their transmission systems.

In case of Eustream the VOTE project is just being implemented as a result this assessment - production of electricity using steam cycle in 5 boilers for 5 combustion turbines connected:

- Electrical power output: 16 to 30 MWe,
- Heating of CS: thermal output 6,17 MWt

The efficiency of gas combustion turbines will be increased from average 35% to almost 50% of the combined cycle.

Literature:

Feasibility study, RWE Plynoprojekt, s.r.o.
Extended Basic Design, Fichtner Energy, s.r.o. Slovakia