QUAD-GENERATION: INTERMITTENCY-FRIENDLY DISTRIBUTED GENERATION CONCEPTS FOR FLEXIBLE PRODUCTION OF ELECTRICITY, HEATING, COOLING, AND FUELS

Morten B. Blarke
Dept. of Energy Technology,
Aalborg University, Denmark
mbb@et.aau.dk

ABSTRACT

The character of local distributed energy systems is set to evolve from co-generation systems (electricity and heating) over tri-generation systems (electricity, heating, and cooling) to Quad-generation systems (electricity, heating, cooling, and liquid or gaseous fuels).

Quad generation represents an integrated state-of-the-art distributed energy plant that may come to provide for all local residential, commercial, industrial energy demands, including transportation fuels.

An innovative Quad-generation concept is presented with variations, an operational dispatch model is developed, optimized using mixed-integer linear programming techniques, and analyzed on an hourly basis with respect to techno-economic consequences, including energy balances, economic costs, CO2 emissions, and intermittency-friendliness.

The paper shows how compression heat pumps and synthetic gas production may be integrated with existing natural gas cogeneration plants. The resulting Quad energy concept is based on 100% renewable energy in terms of local fuel consumption, eliminates CO2 emissions, and supports improved system integration for intermittent renewables and distributed generation. Optimal designs are presented for supporting cost-effective integration.

Economic lifecycle costs are currently not competitive at projected energy price and market variance levels.

Keywords: Quad generation, 100% renewable distributed energy systems, synthetic natural gas, large-scale dual-mode heat pumps, techno-economic optimization.

INTRODUCTION

Distributed cogeneration is under pressure in energy systems with increasing penetration levels for intermittent renewables. In West Denmark, since 2005, high gas prices, and lower electricity prices have been forcing operators away from co-generation towards heat-only boiler operation jeopardizing the efficiency potential inherent to cogeneration.

This paper introduces and evaluates a concept for Quad-generation [1] by which a combination of electricity, some of which is self-generated, and biomass, here agricultural straw, is converted to produce all four basic energy services: electricity, heat, cooling, and liquid or gaseous fuels.

While Quad-generation could be admired for its ability to supply all basic energy services in island-mode, the concept may also support an energy strategy for integrating intermittent renewables and high-efficiency distributed generators in meeting local thermal demands for heating and cooling.

Quad-generation options are investigated with respect to economic cost-effectiveness, system-wide CO2 emissions and intermittency-friendliness.

METHODOLOGY AND ASSUMPTIONS

The continued operation of an existing CHP plant is compared to three Quad options (Table 3). While not being limited to this particular combination of processes, Quad-generation here combines straw-fuelled gasification, syngas-fuelled engine and boiler (re-using existing natural gas fuelled assets), electrolyzer and methane synthesis, compression heat pump (HP), and thermal storages. The plant produces electricity, district heating and cooling, and synthetic natural gas (SNG). Electricity is traded in the spot market, and SNG is traded in the annually uniform market for natural gas.

Optimal solutions are identified according to the principles listed in Table 3, systematically varying HP and SNG capacities. Each option is investigated with respect to capacity variations for operation in 2013 on the basis of which pre-optimal process capacities are suggested. The resulting options are optimized on an hourly basis using a weekly planning horizon for each year of operation over a 20 year planning period (2013-2032) on the basis of projected deterministic weekday-synchronized sets of hourly parameters.

Each case is modeled using COMPOSE [2, 3], which allows for techno-economic operational optimization using mixed-integer linear programming (MILP) of complex poly-generation options embedded within gas and electricity markets. In COMPOSE, these markets are defined by marginal producers operating under assumptions that are shared with the option being analyzed, allowing for consistent endogen system analysis.

Each MILP program is formulated according to the standard formulation presented in Eq. (1):

$$\text{minimize } f(x) = \sum_{hour=1}^{8760} operational\ cost_{year,hour} \quad (1)$$

subject to linear constraints and bounds, incl. integrality constraints

COMPOSE identifies the plant design's optimal operational strategy by minimizing the economic cost of operation under constraint of annual and hourly deterministic projections for thermal energy requirements, O&M costs, unit capacities, and electricity and SNG markets. Fiscal costs are excluded and CO2 credits, if any, are not internalized. There are no input-output constraints on markets and thermal storages. A detailed description of the modeling framework and the operational optimization programming techniques is provided in [4].

The district heating requirements are based on 2010 recorded requirements from a Danish distributed co-generation plant with 1260 heating consumers [5]. The district cooling requirements are estimated based on what could be the process cooling requirements of the area's commercial buildings. The hourly distribution of cooling requirements is assumed to be uniform as would be the case for computer server rooms, one possible end-use for process cooling.

Projected annual fuel and electricity costs are based on projections published by the Danish Energy Authority [6]. Investment costs and O&M costs are based on today's technology using a combination of findings in [7] and [8]. All investments are considered fully depreciated over the planning period. For discounting investments, an economic discount rate of 3% p.a. is applied Table 1, Table 2, Table 3, and Table 4 summarizes key parameters.

The cases are also compared by their intermittency-friendliness coefficient *Rc*. Blarke [9] has introduced the system-specific measure *Rc* for evaluating the intermittency-friendliness of an electricity producer or end-user. *Rc* is defined as the statistical correlation between the net electricity exchange between producer (and/or consumer) and grid *e*, and the energy system's net electricity requirements *d* (Eq. (2)).

$$R_c = \frac{\sum (e-e_m)(d-d_m)}{\sqrt{\sum (e-e_m)^2 \sum (d-d_m)^2}} \quad (2)$$

where subscript *m* refers to the mean value.

The net electricity requirement is defined as the electricity demand minus the intermittent electricity production. *Rc* serves to evaluate the marginal "goodness" of a plant's or end-user's response to variations in net electricity requirements ranging from -1.0 to 1.0 for each year of operation.

The cases are furthermore compared by their system-wide technical CO2-emissions, where emissions due to purchase, and avoided emissions due to selling, are found by identifying the marginal producer in each hour of operation according to the spot market and the short-term operational costs of a series of system-specific candidate plants. In this case, system-specific candidate plants include CCGT, Coal, Hydro/Nuclear/Wind. Avoided emissions due to SNG supplied to the gas market are internalized, assumingly replacing the consumption of natural gas. Methodologically, technical CO2 reductions ignore a well-functioning carbon emission reduction (CER) market under which any electricity sector changes would not impact absolute emissions in a quota system controlled by absolute values.

A number of methodological concerns must be raised: Notably, deterministic hourly profiles are normalized 2011 statistics for wind production, electricity demand, spot market, and week-day synchronized heating and cooling demand profiles for 2010. The major sensitivity lies with using 2011 statistics. In fact, a major sensitivity lies in using historical statistics at all. However, at this point, it is hard to believe that anyone can really predict future electricity and gas markets anyway. So the results of the study should basically be interpreted as a realistic basis for an investment decision made for 2013 on the basis of information and sensible projections or historical data available in 2012.

The projected price ratio between electricity and coal and gas is significantly influencing the operational strategies of every plant in the system and the resulting system-wide energy, economic, and environmental consequences. This issue has been dealt with in [10]. In 2013, the GE-ratio (electricity over natural gas price) was 0.82, which tend to lead to more intermittency-friendly outcomes. According to the price projections, the GE-ratio increases to 1.06 in 2024, but will fall back to 0.81 by 2032. Basically this would tend to support the hypothesis that the results here will not tend to overestimate the level of intermittency-friendliness.

Also, it must be acknowledged that while the system's annual electricity demands and intermittent production increases according to the projections in COMPOSE, the hourly electricity spot market profile is constant and deterministic in all years. If this profile would have greater statistical variance and a distribution towards price extremes it would promote the relative advantage of adding further operational flexibility, typically achieved by adding new processes, increasing the capacity of existing processes, or by adding heat or cold storage, gas storages, or, while not considered here, electricity or liquid fuel storages.

Table 1: District heating and cooling demand parameters.

Parameter	**Annual [MWh/yr]**	**2013-2032 annual mean projection**	**Hourly distribution in each year**
District heating demand	37,200	Constant	2010 distribution (Fig. 1)
District cooling demand	5,000	Constant	Uniform (Fig. 1)

Table 2: Fuel and electricity cost-benefit parameters. *Excluding trading costs and Public Service Obligations (PSO costs).

Parameter	**2013-2032 annual mean projection**	**Hourly distribution in each year**	**Variable T&H/T&D**
Straw cost	Fig. 2	Uniform	€4.6 /MWh
Electricity spot market	Fig. 2	2011 distribution (Fig. 3)	€20.1 /MWh*
SNG market	Fig. 2	Uniform	-

Table 3: Technical design variables and cases.

Base Case: Existing CHP [5]	**Capacities and conversion efficiencies**
Existing CHP engine	8.2 MW-heat ($\eta_{natural\ gas\ to\ electricity}$=0.405, $\eta_{natural\ gas\ to\ heat}$=0.5357)
Existing heat-only boiler	8.15 MW-heat ($\eta_{natural\ gas\ to\ heat}$=1.03)
Existing hot thermal storage	1,600 m^3 (ΔT=50°) with thermal heat losses [11]

Case A: Quad-generation NPV optimal	
Existing CHP engine on syngas	6.15 MW-heat (capacity is 25% lower than on natural gas, identical efficiencies)
Existing boiler on syngas	6.1 MW-heat (capacity is 25% lower than on natural gas, identical efficiencies)
New straw gasification unit	10 MW-syngas ($\eta_{straw\ to\ syngas}$=0.81, $\eta_{straw\ to\ heat\ recovered}$=0.10). Minimum for supplying sufficient fuel with minimum heat pump to supply district heating.
New electrolyzer, CH4 synthesis	9 MW-SNG ($\eta_{syngas\text{-}electricity\ to\ SNG}$=0.86, 95/5 syngas-electricity ratio). Analyzed for 0 to 15 MW-SNG. Minimized operational cost.
New cold thermal storage	1,600 m^3 (ΔT=20°) without thermal losses. Matching volume of hot thermal storage.
New compression heat pump	1 MW-heat ($COP_{electricity\ to\ heat}$=2.5, $COP_{electricity\ to\ cooling}$=1.5). Minimum heat pump to supply cooling.

Case B: Quad-generation *Rc* optimal	As Case A, but with 2 x thermal storages and 2,000 MWh syngas storage cost-effectively. Analyzed for 1 to 15 MW-heat heat pump.

Case C: Quad-generation operational costs optimal	As Case A, but with unlimited thermal and syngas storages and 7 MW-heat heat pump. Analyzed for 0 to 150 MW-SNG.

Table 4: Key economic investment and operational cost parameters.

Parameter	**Specific investment**	**Fixed operational**	**Variable operational**
Existing CHP engine	-	-	€8.6 /MWh-elec, €10 /Startup, continuous operation down to 50%.
Existing heat-only boiler	-	-	€1.3 /MWh-heat
Straw gasification unit	€2.4M /MW-syngas	€78,000 /MW-syngas	-
CH4 synthesis, electrolyzer	€1.4M /MW-SNG	-	-
Cold storage	€0.125M / 1,000 m3	-	-
Compression heat pump	€0.57M /MW-heat	-	€8.0 /MWh-heat, €0.4 /Startup, continuous operation down to 10%.

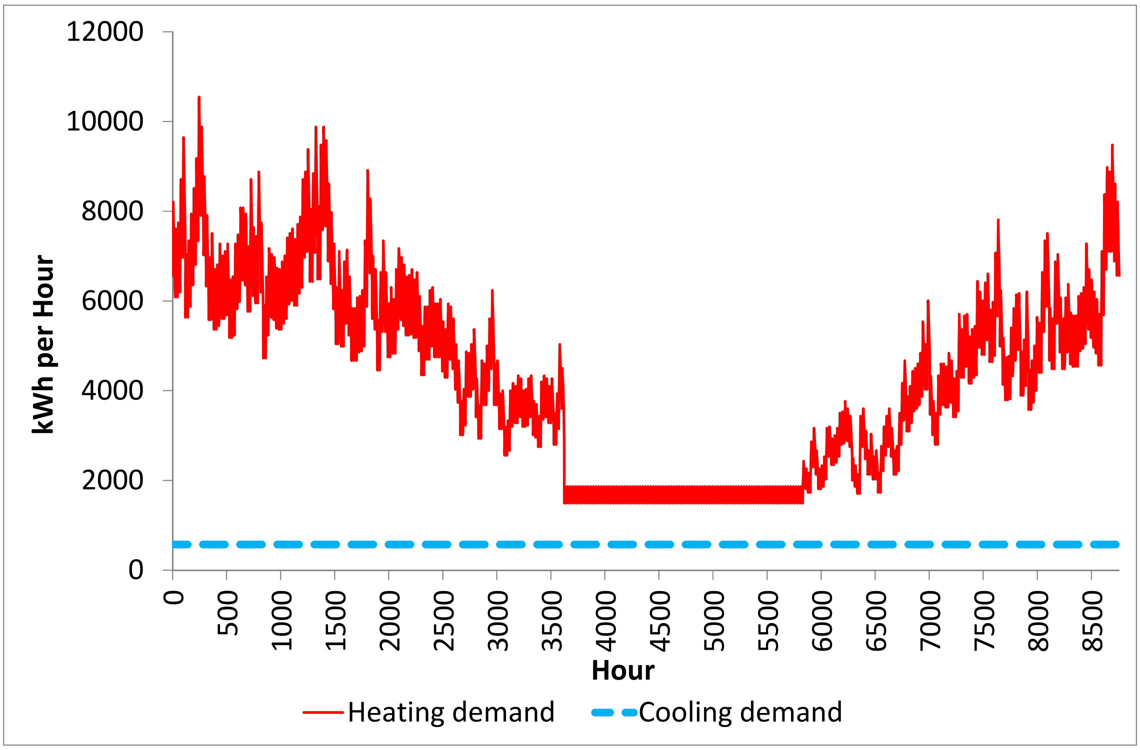

Fig. 1: Projected hourly deterministic parameter distributions of heating and cooling demands. Hourly distribution of heating demand is based on 2010-historical data, while the uniform hourly distribution of district cooling demand is based on what would likely be the requirements of the area's commercial buildings, e.g. computer server rooms.

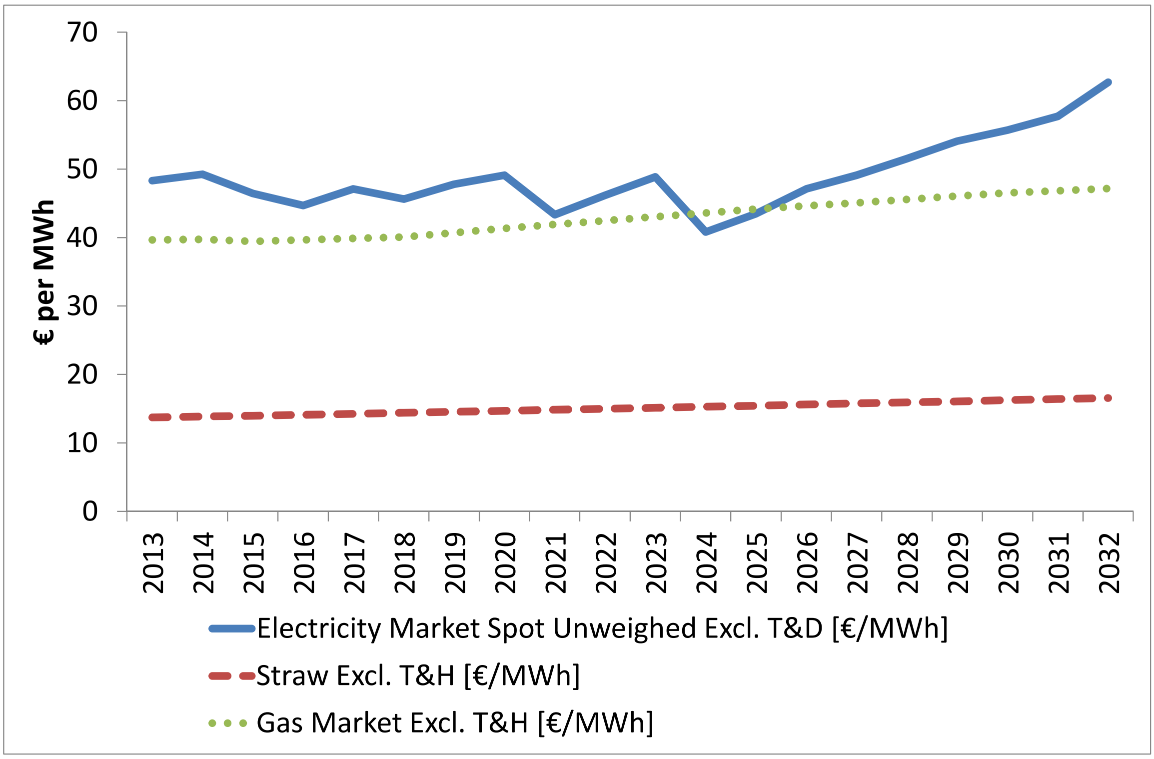

Fig. 2: Projected unweighted annual mean prices for straw (excl. T&H costs), SNG (as natural gas), and electricity spot (excl. T&H costs).

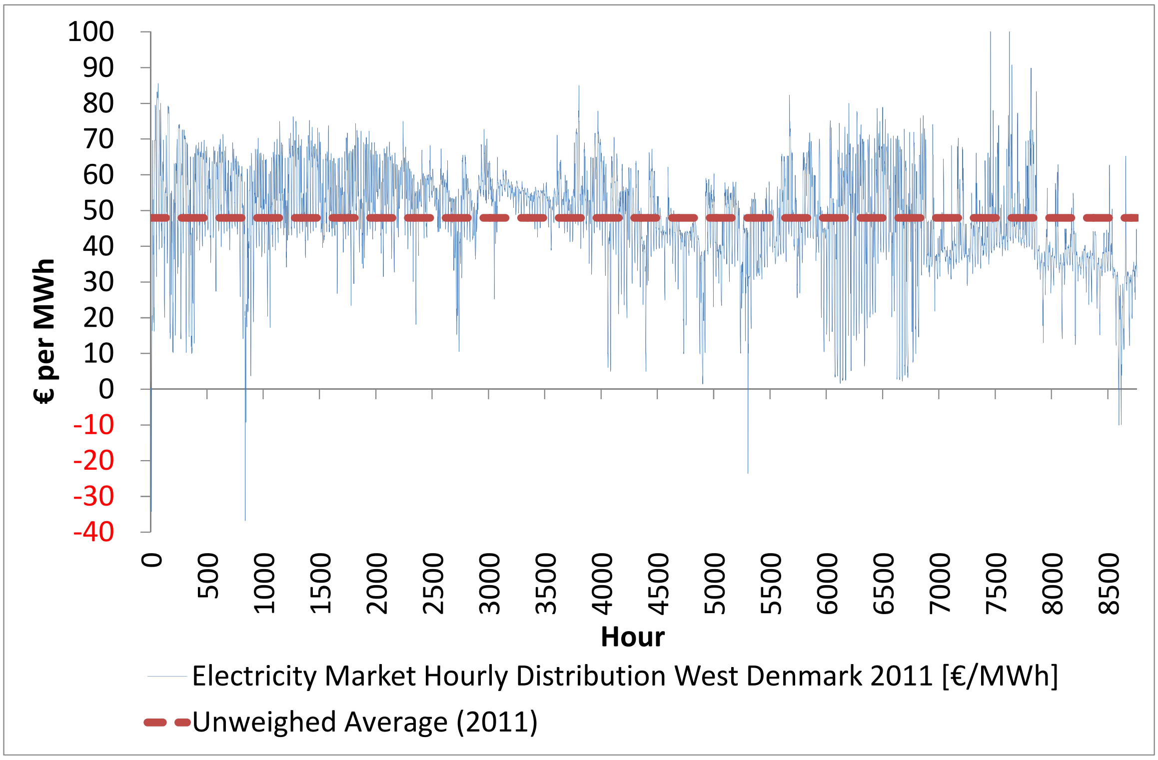

Fig. 3: Projected hourly deterministic parameter distribution of electricity prices in all years based on West Denmark's spot market in 2011.

RESULTS

The Base Case (continued operation on natural gas) was compared to three straw-fuelled Quad options with pre-optimal capacities over a 20-year planning period subject to deterministic projections. Pre-optimal capacities for the three Quad options were arrived at by means of results illustrated in Fig. 4 to Fig. 7. HP and SNG capacities were systematically varied to arrive at optimal capacities for 2013 operation. These capacities were subsequently used as pre-optimal.

Fig. 4 shows that Quad-generation offers a significant potential for reducing operational costs in 2013. The Base Case operational costs totals €1.35 mill leaving heating and cooling un-valued, while:

- Quad-Case A reduces costs by 8% to 29% (increases with increasing SNG capacity to maximum)
- Quad-Case B reduces costs by 30% to 38% (increases with increasing HP capacity to maximum)
- Quad-Case C reduces costs by 15% to 44% (increases with increasing SNG capacity to maximum).

For Case A, SNG capacities above 9 MW do not further reduce operational costs. For Case B, HP capacities above 6-7 MW do similarly not significantly further reduce operational costs.

Taking investment costs into account, Quad generation results in higher levelized costs of operation as shown on Fig. 5. Case A with minimum HP and minimum SNG represents the most NPV cost-effective Quad option, but more than doubles the levelized costs from €39.2 (Base Case) to €98.9 per MWh-heat assuming that the cooling has zero value.

Fig. 6 shows the resulting system-wide technical CO2 emissions. It is found that all Quad options offer a significant potential for eliminating local emissions from previous use of natural gas, and reduce from a somewhat symmetrically similar scale due to replaced fossil fuel consumption in the gas and electricity markets. It is noticed how increasing capacities of HP and SNG results in lowering the emission reduction potential. This must be considered an adverse, or perhaps even perverse, effect, and is explained by the adverse impact of reducing distributed electricity generation in a relative low mean price electricity market characterized by competing CCGT, Coal, and Hydro/Nuclear/Wind. However, 2013 emission reductions are significant, dropping from 3,500 ton for the Base Case to Case A's negative -4,200 ton with optimal capacity,

Fig. 7 shows the resulting system-specific intermittency-friendliness *Rc*. Case A results in a lower *Rc*, while Case B and C results in a higher *Rc*. Why is *Rc* lower for Case A, making it *less* intermittency-friendly? This is due to the operational constraints given by the minimum size HP and the existing thermal storages. The heat pump basically needs to operate at full capacity continuously for supplying cooling. And why is *Rc* higher for Case B and C, making these *more* intermittency-friendly, far more than the Base Case, and certainly far better than Case A? The reason is that Case B and C introduces relaxed operational constraints given by increased, and in this respect also optimal, HP and SNG capacities, intermediate syngas storage, and larger near optimal thermal storage volumes.

It is furthermore found that capacities that are optimal in terms of operational costs are practically also optimal in terms of *Rc*. The reason is that historical spot markets are statistically correlating with historical net electricity demands, i.e. the electricity demand minus intermittent production which is also used when calculating *Rc*. This correlation is representing a techno-economic upper limit to *Rc* when the option is optimized for operation in such markets.

The Sankey diagrams in Fig. 8 to Fig. 11 illustrate the energy balances in 2013 for the Base Case and Cases A, B, and C.

For Case A, the highlights are:

- Straw consumption totals 97.8 GWh, or 27,000 tons, corresponding to the annual output from 8,500 ha of agricultural land corresponding to 0.3% of Denmark's farmed land in 2010.
- The plant sells 10.4 GWh electricity and purchases 3.6 GWh electricity.
- The plant sells 41.4 GWh SNG, or 3.8 mill. Nm^3, corresponding to 0.06% of Denmark's natural gas consumption in 2011.
- The CHP engine's share of total heat production is 45%, the heat pump's share is

23%, while the heat-only boiler's share is 6.5%.

- The system-wide fuel-to-energy efficiency is 93%, found by dividing heating and cooling production divided by the system-wide primary fuel consumption.

Table 5 compares selected results for the Base Case with Cases A, B and C. It is found that the amount of sold electricity is significantly lower for Quad generation, and is further reduced with increasing operational variability. While the Base Case produces 16.6 MWh electricity, Case A's net electricity supply is reduced by 60%, Case B by 80%, and Case C by 87%. Electricity purchase is increasing with increasing operational variability, highest for Case C. Total grid-exchanged electricity (sold plus purchased electricity) is reduced by 27% from the Base Case to Case C. It is found that increasing HP and SNG capacities results in an increased share of heating being produced by the HP as well as increased SNG production.

Fig. 12 to Fig. 15 show results for the Base Case, and the Cases A, B, and C, over a 20-year planning period (2013 to 2032) subject to deterministic projections.

Fig. 12 shows that the operational costs for the Base Case are increasing over time, while the operational costs for Quad options are being reduced over time, mainly due to the increased value of SNG. Case C results consistently in 50% operational cost reductions.

Fig. 13 shows that that all Quad options results in higher levelized costs per produced unit of heat (with un-valued cooling). At €180 per MWh-heat, Case A is the more cost-effective Quad option, though 2.5 times higher than the Base Case.

Fig. 14 shows that Quad-generation leads to significant system-wide technical CO2 reductions over the planning period. Case A in particular is delivering significant and stable system-wide CO2 reductions, while Cases B and C are delivering less significant reductions and are more susceptible to year-to-year variations. The annual variations are caused by changes in the fuel mix in central electricity generation. The unit scheduling explains the annual variations which are due to projected fuel and electricity prices, and the projected intermittent renewables generation and electricity demand for the system in which the Quad-generation project is embedded.

Fig. 15 shows that while all cases are subject to falling intermittency-friendliness *Rc* over time, the relative improvement potential is maintained over the planning period. Cases B and C offer a significant potential for increasing *Rc*, while Case A results in a lower *Rc*. While Case A is the most cost-effective Quad-design in terms of lifecycle costs (NPV), it does not provide any improved operational flexibility nor improved spot market responsiveness. The result shows that these constraints may be relaxed by adding syngas storages, increasing production capacities, and increasing the volume of thermal storages (Cases B and C). However, such relaxations are resulting in higher investment costs without any significant improvements in operational benefits, thus jeopardizing the economic feasibility of Quad-generation.

Table 5: Selected 2013 energy balance results.

Result / Case	Base	A	B	C
Straw consumption [MWh]	-	97.7	98.4	108
Electricity sold [MWh]	16.6	10.3	7.7	7.2
Electricity purchased [MWh]	-	3.6	4.2	5.1
SNG production [MWh]	-55.8	41.6	47.0	58.8
Heat pump share of heating [%]	-	22.6%	33.7%	33.5%
System-wide fuel-to-energy efficiency [%]	132%	93%	94%	89%

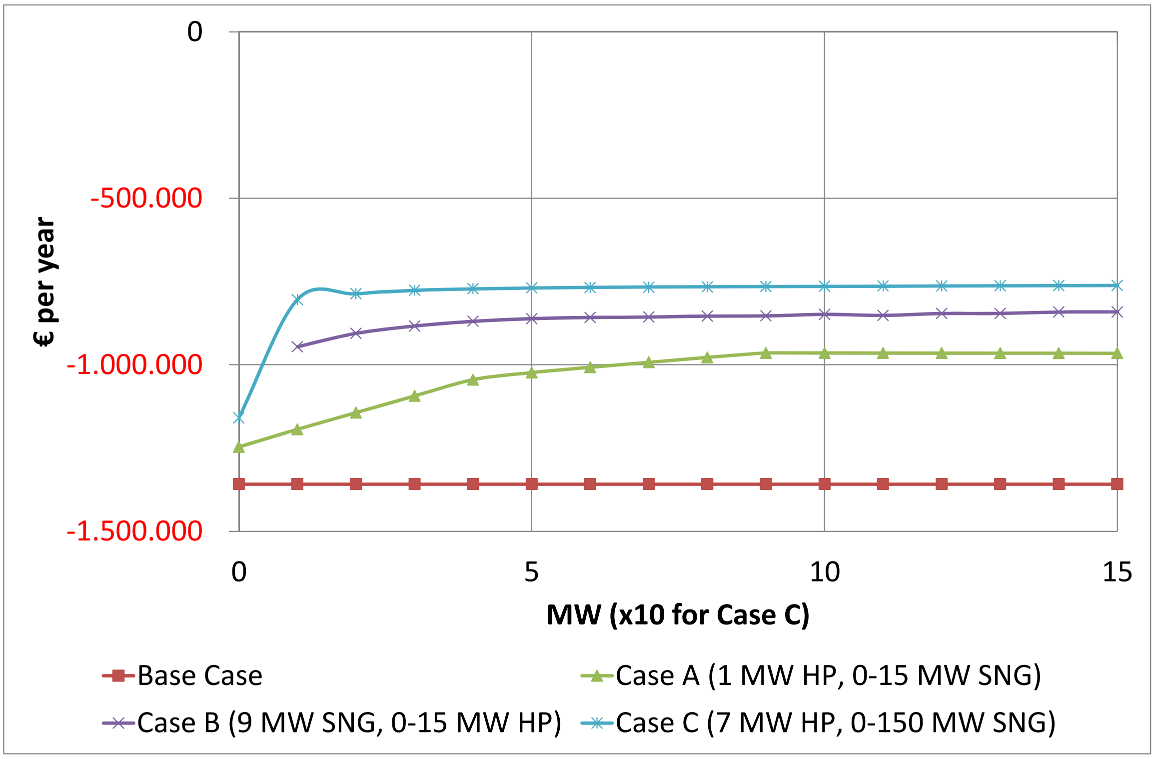

Fig. 4: Economic operational costs in 2013 excluding investment costs and fixed costs.

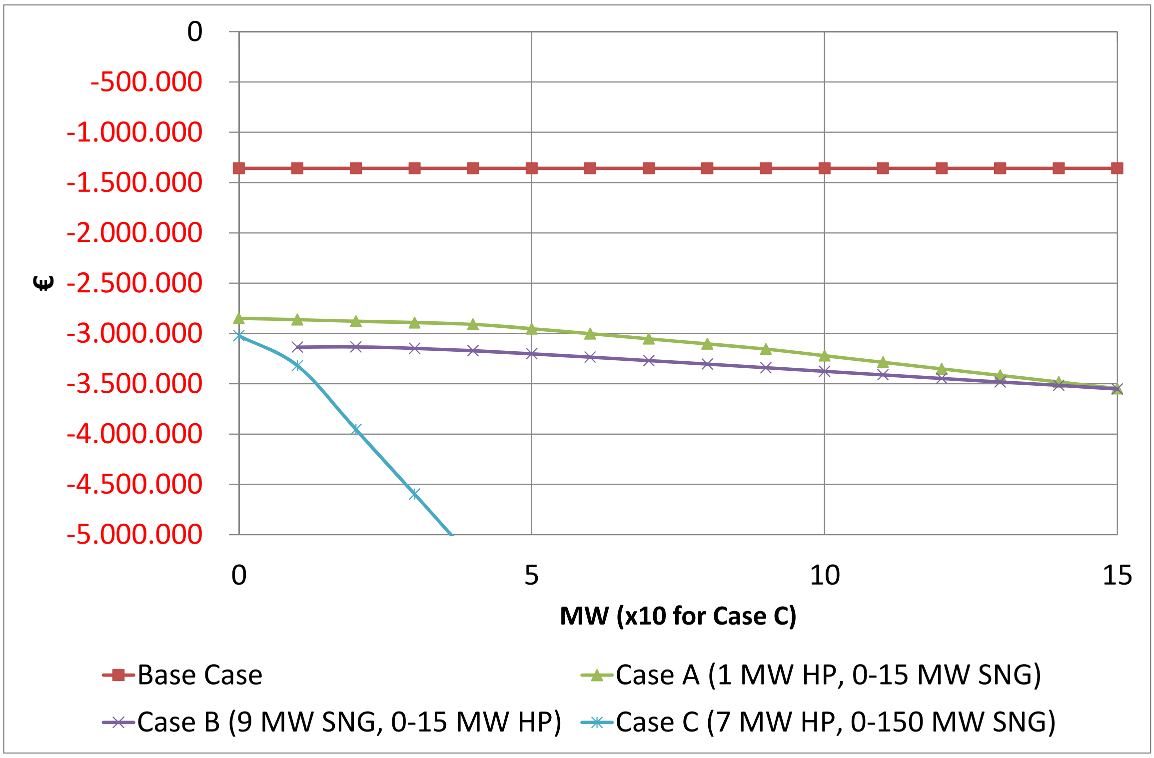

Fig. 5: Economic costs in 2013 including levelized investment costs and fixed costs.

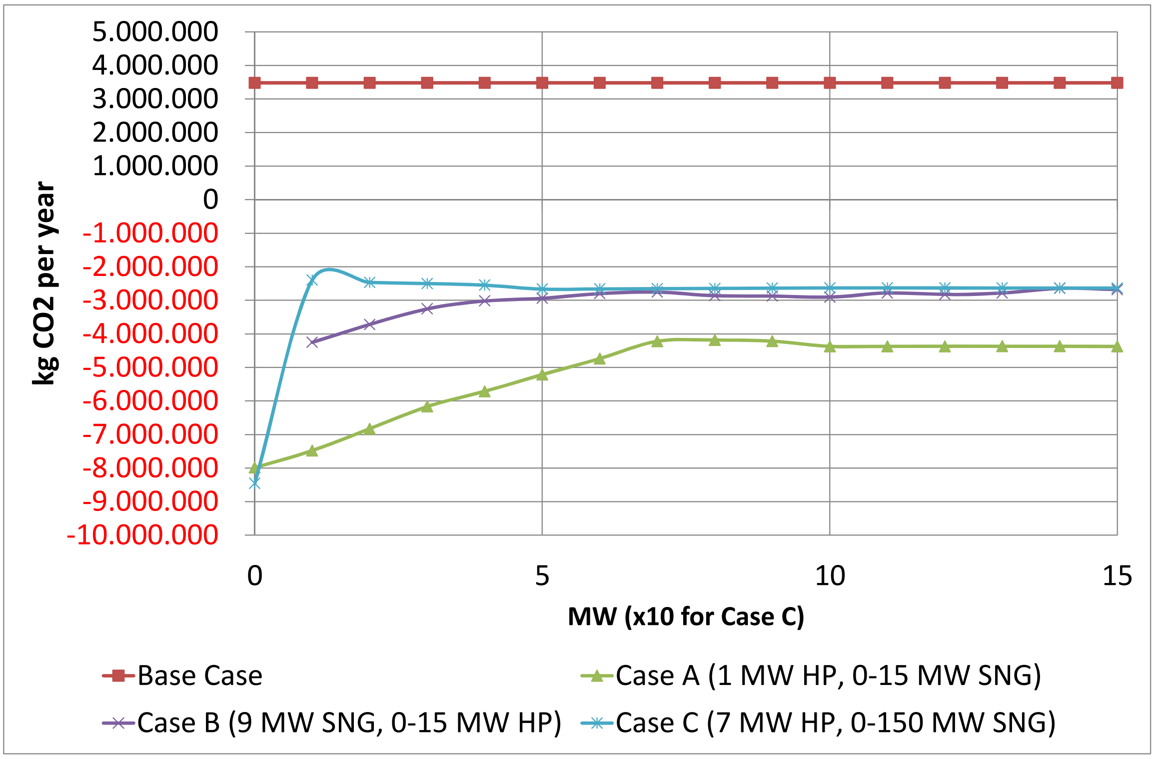

Fig. 6: System-wide CO2 emissions in 2013.

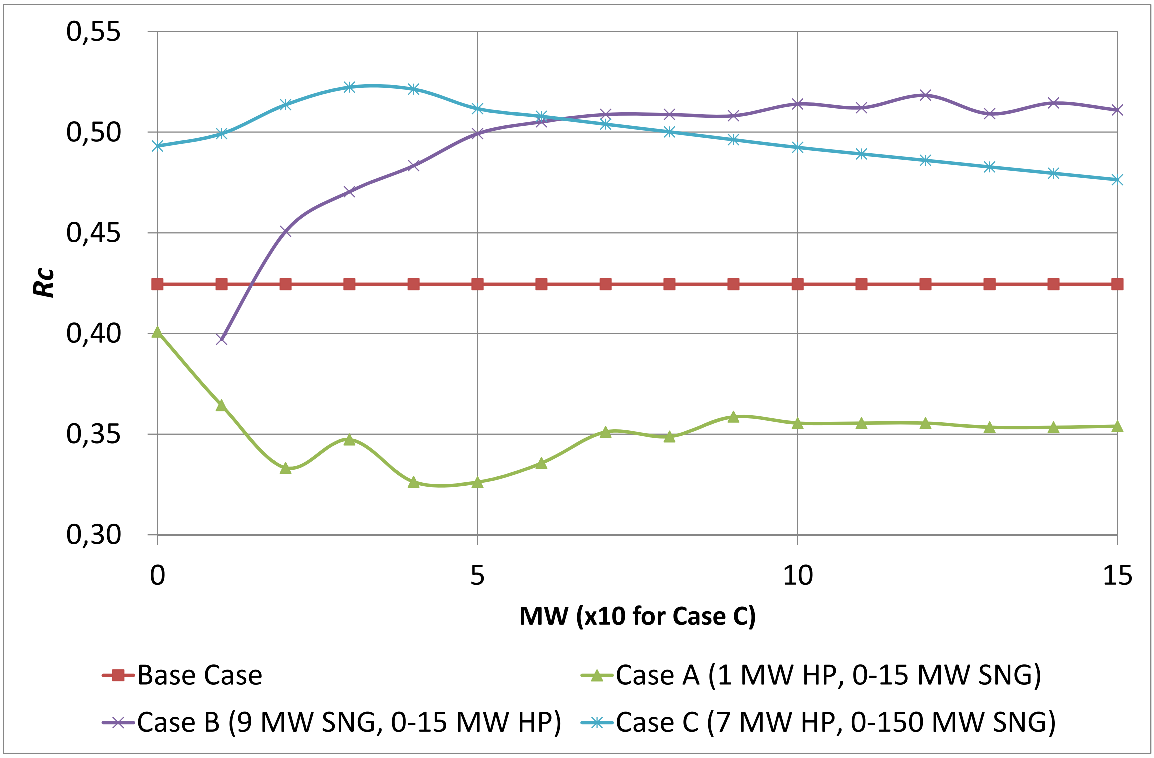

Fig. 7: Intermittency-friendliness *Rc* in 2013.

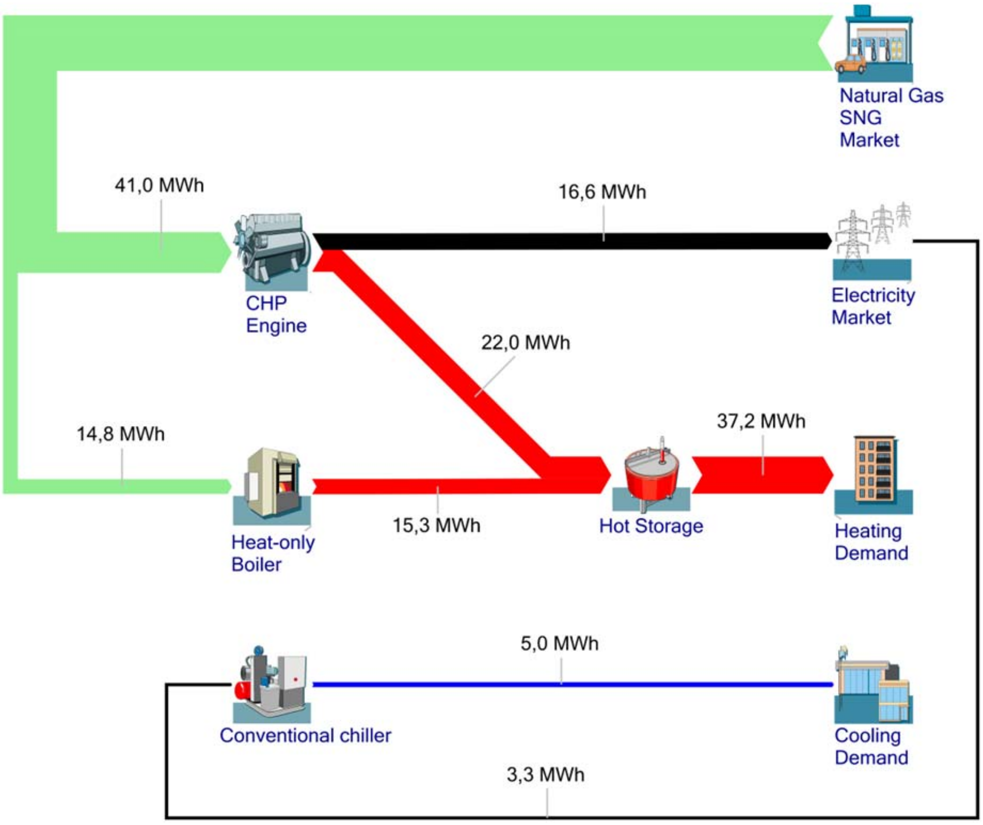

Fig. 8: Existing natural gas fired cogeneration 2013 energy balance (Base Case).

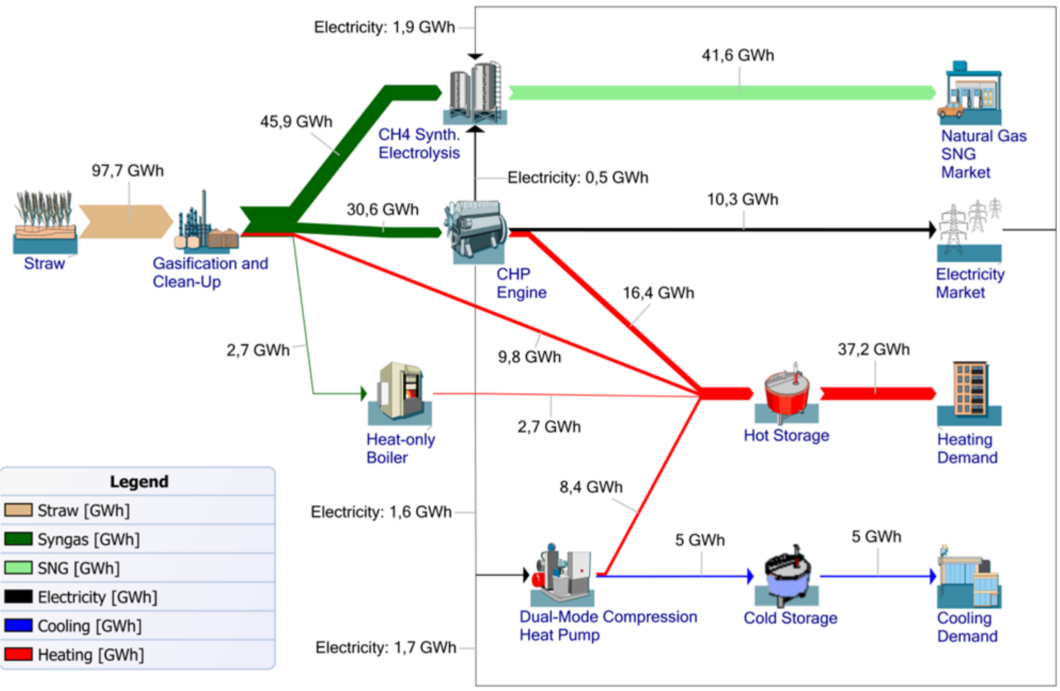

Fig. 9: Quad-concept 2013 energy balance (Case A: Cold storage, 1 MW-heat HP).

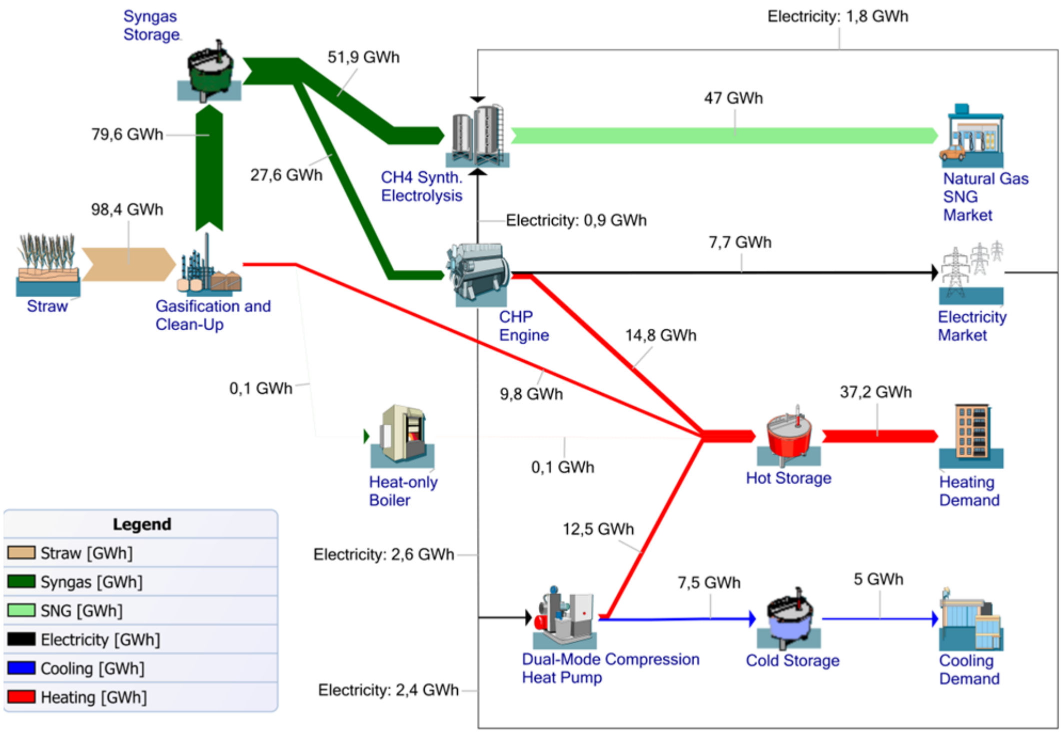

Fig. 10: Quad-concept 2013 energy balance (Case B: Syngas storage, 7 MW-heat HP).

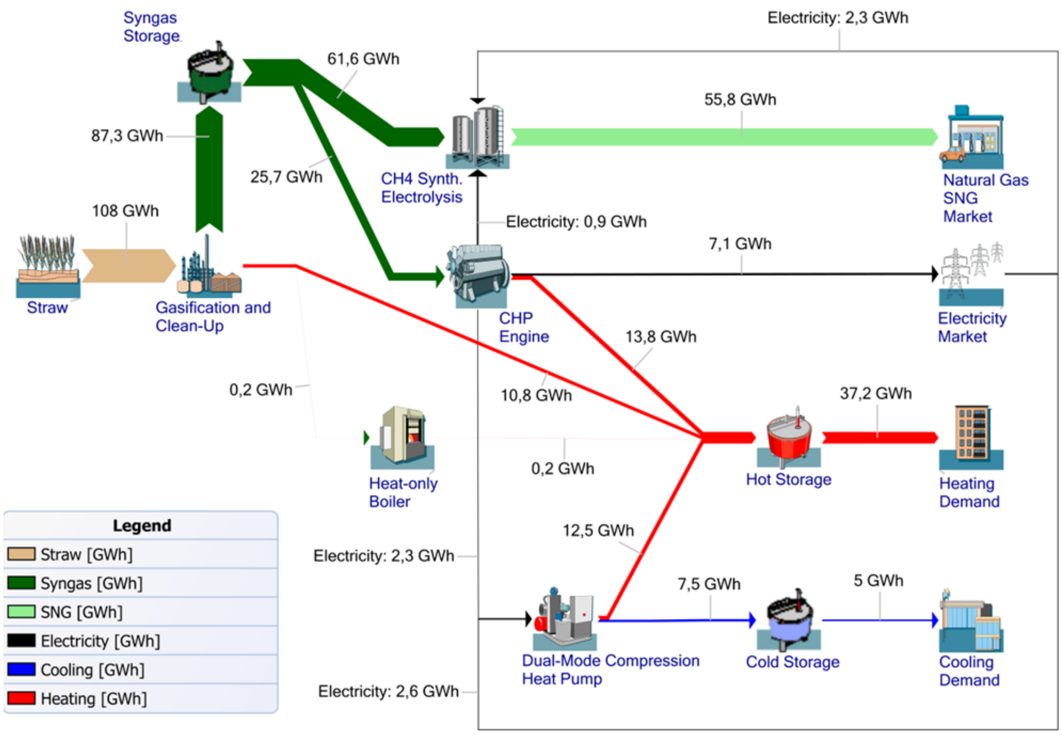

Fig. 11: Quad-concept 2013 energy balance (Case C: 7 MW-heat HP, 40 MW SNG).

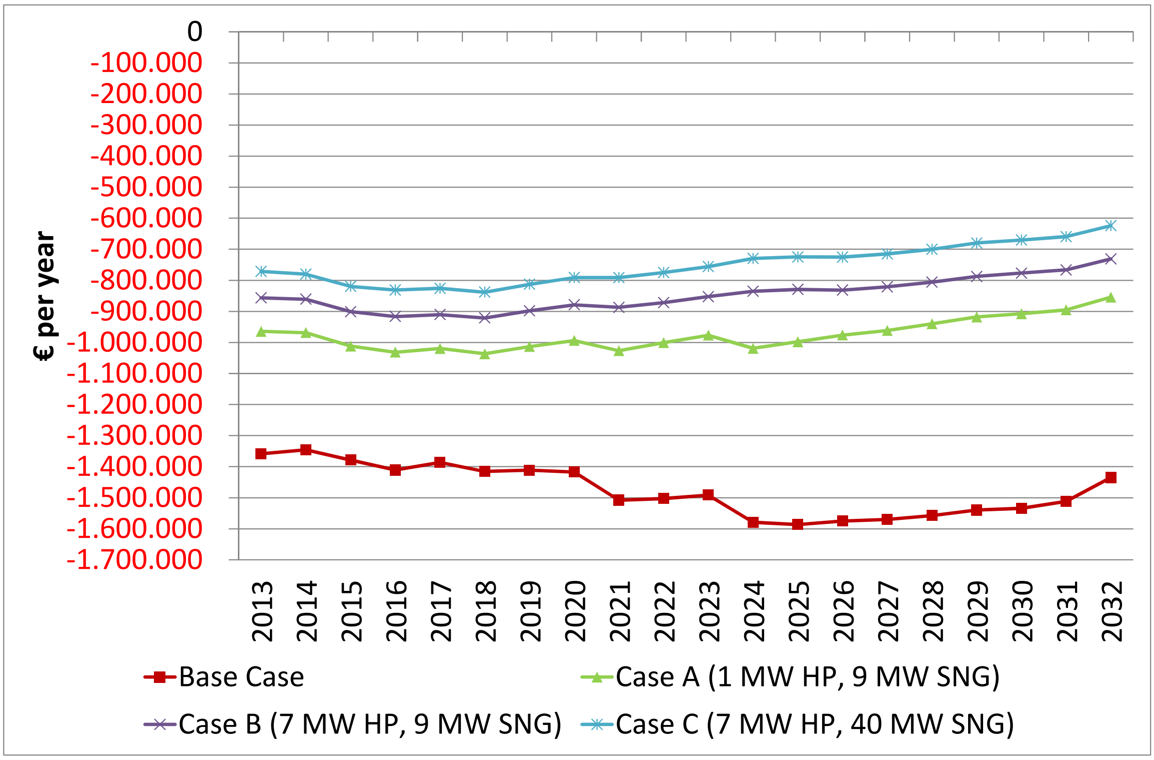

Fig. 12: Economic operational costs 2013-2032 with un-valued heating and cooling.

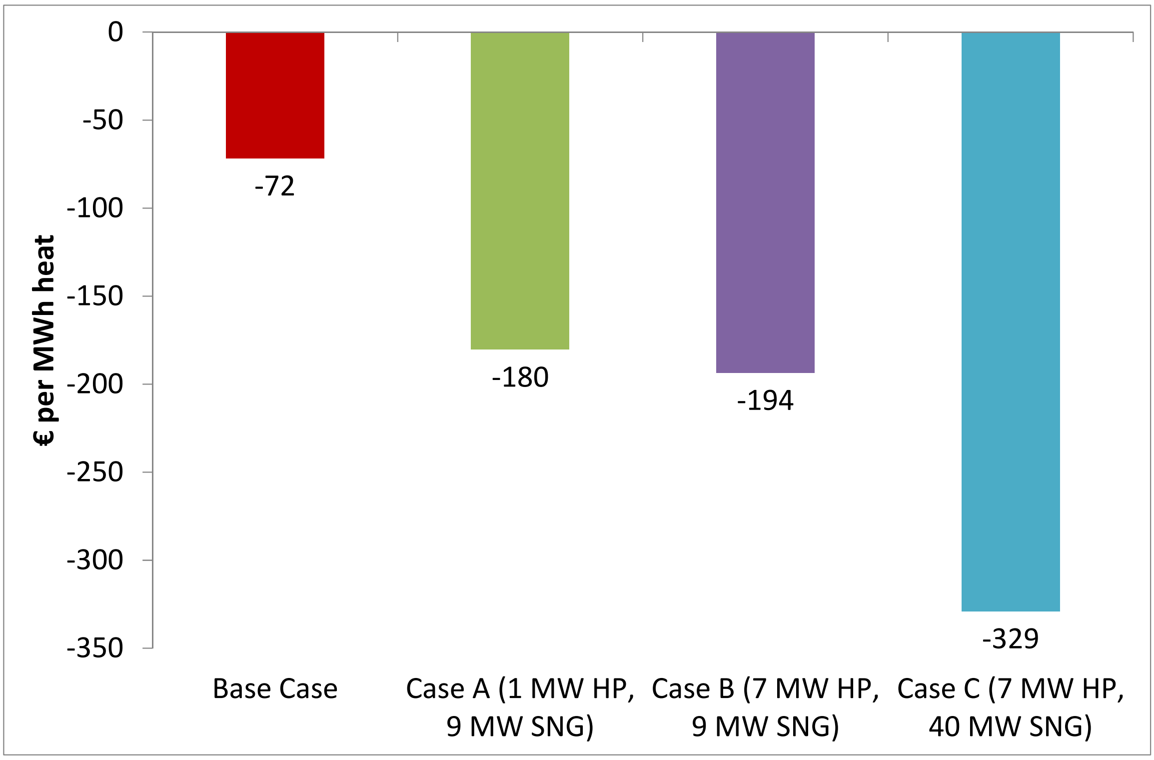

Fig. 13: Economic levelized costs per unit heating with un-valued cooling using an economic discount rate of 3 % p.a.

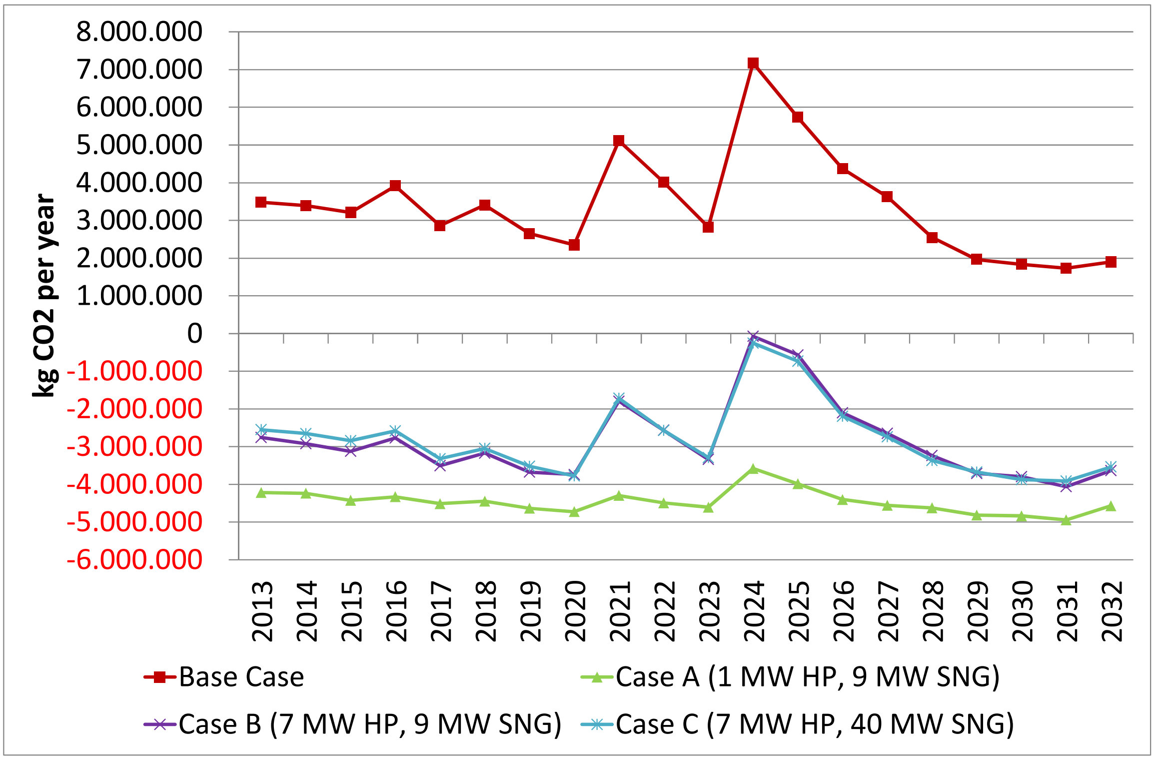

Fig. 14: System-wide CO2 emissions 2013-2032.

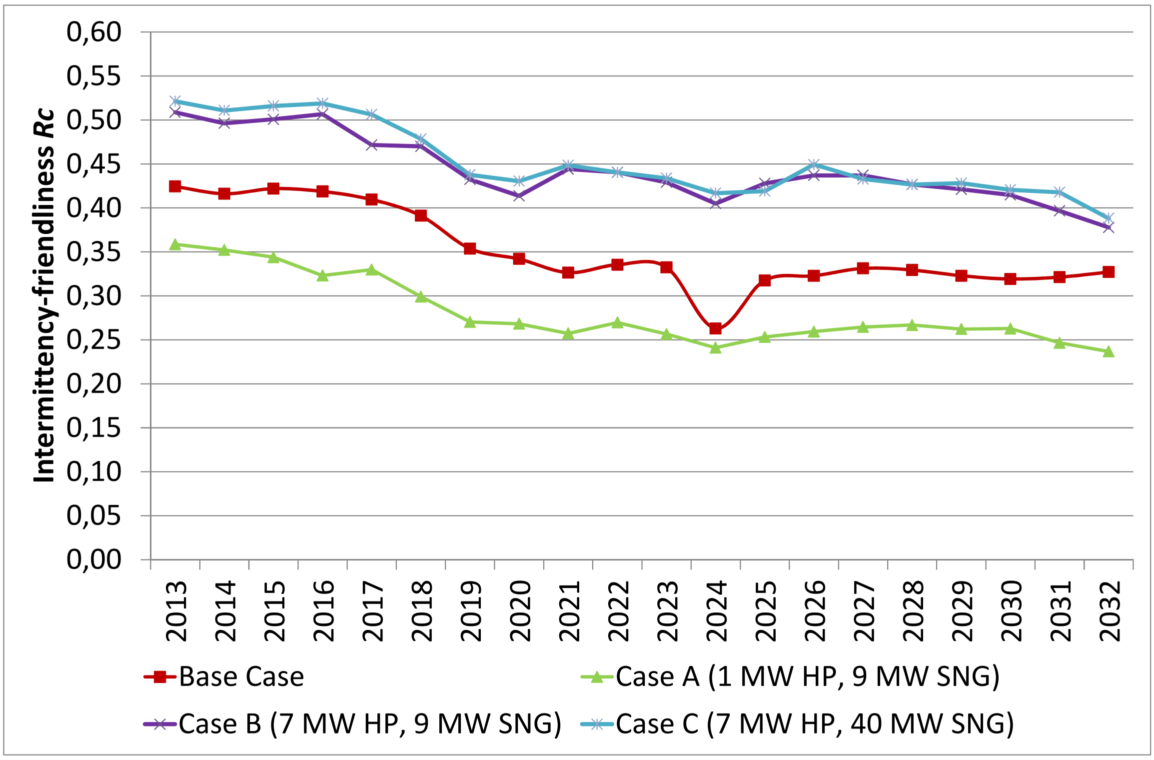

Fig. 15: Intermittency-friendliness *Rc* 2013-2032.

CONCLUSION

The paper investigates the techno-economic performance of an innovative straw-fuelled concept for Quad-generation that supplies all four basic energy services: electricity, heat, cooling, and liquid or gaseous fuels. This could be an attractive sustainable energy option for high-efficiency and intermittency-friendly distributed generation systems, or a basis for islanding-mode micro-grid operation.

Three Quad options were designed and compared to the continued operation of a natural gas fired cogeneration plant in district heating. The plant's existing gas engines, heat-only boiler, and thermal storage, are kept and operated under the Quad options.

As such, the paper shows how compression heat pumps and SNG production may be integrated with existing natural gas fired cogeneration.

The options were investigated with respect to economic cost-effectiveness, system-wide CO2 emissions and intermittency-friendliness.

It is found that the levelized economic costs of heat production are at least 2.5 times higher for Quad generation. If capital costs are not reduced, it may be speculated that Quad-generation could be feasible in future markets not captured by the current projections. For example, if electricity spot markets are affected by a combination of extreme penetration levels for intermittent renewables, and limited options for domestic and transnational balancing, the greater price spread may more significantly benefit the operational flexibility of Quad generation. Such development is possibly preconditioned by a prioritized domestic integration strategy for intermittent renewables (SmartGrid) [13]. In other words, such potential fuel and electricity markets would be characterized by high price variability. This would favor Quad-generation relatively over options with a lower degree of operational flexibility, like conventional co-generation.

While suffering in terms of economic costs, it is found that Quad-generation holds a significant potential for technical system-wide CO2 reductions and represent a significant option towards eliminating fossil fuel consumption in the energy sector. However, the resulting CO2 reduction cost of €281 per ton is significantly higher than today's low carbon credit prices in the European Trading System [12].

It is furthermore found that the intermittency-friendliness *Rc* for Quad-generation and existing CHP co-generation are both subject to falling rates. While these options are supporting wind integration, they are becoming less able to do so at increasing wind penetration levels as projected for West Denmark. This is an important reminder that distributed co-generation is under pressure to innovate in energy systems with high penetration levels of intermittent renewables.

The relatively lower intermittency-friendliness *Rc* for Case A compared to the Base Case is reversed to a significantly higher *Rc* in Case B and C by introducing syngas storage, increasing production capacities, and increasing the volume of thermal storages.

Thus, the analysis finds that advanced intermittency-friendly Quad-generation (Case B and C) is a pathway for optimal co-existence between the biomass energy resource, and intermittent renewables, such as wind and solar power.

Operators in distributed co-generation are forced to innovate in order to maintain any significant level of co-existence between distributed cogeneration and intermittent renewables. Either they can assume a reactive role, possibly even giving up co-generation introducing heat-only options, including solar heating and biomass boilers. Or they can take more actively part in developing solutions that will enable extreme penetration levels for both intermittent renewables and distributed co-generation and Quad-generation. This is the path to a fossil free and high efficiency energy system.

NOMENCLATURE

1€	7.45 DKK, 1.3 USD (August 2013)
CHP	Combined Heat and Power
COP	Coefficient of Performance
EIRR	Economic Internal Rate of Return
O&M	Operation and maintenance (costs)
PSO	Public Service Obligations
Rc	Relocation Coefficient, Intermittency-Friendliness
SNG	Synthetic Natural Gas
TRI	Tri-generation (Combined Heat, Cooling, and Power)
T&D	Transmission and distribution (costs)
T&H	Transportation and handling (costs)
η	First law efficiency

NPV	Net present value
HP	Heat pump
ΔT	Thermal storage temperature difference

ACKNOWLEDGMENTS

The paper is a corrected and expanded version of the conference paper “QUAD-Generation: Techno-Economic Analysis Of A 100% Renewable Energy Plant For Flexible Local Production Of Electricity, Heating, Cooling, And Fuels” presented at the Third International 100% Renewable Energy Conference (IRENEC2013) in Istanbul, Turkey, June 27-29, 2013 [14].

REFERENCES

[1] S. Rudra, L. Rosendahl, M.B. Blarke, Proposal of a biomass based Quadgeneration system for power, heat, cooling and SNG production, International Journal of Green Energy (Under review).

[2] M.B. Blarke, Compare Options for Sustainable Energy (COMPOSE). Download from http://energyinteractive.net (2013).

[3] D. Connolly, H. Lund, B.V. Mathiesen, M. Leahy, A review of computer tools for analysing the integration of renewable energy into various energy systems, Applied Energy. 87 (2010) 1059-1082.

[4] M.B. Blarke, E. Dotzauer, Intermittency-friendly and high-efficiency cogeneration: Operational optimisation of cogeneration with compression heat pump, flue gas heat recovery, and intermediate cold storage, Energy. 36 (2011) 6867-6878.

[5] M.B. Blarke, Data recieved from Brovst district heating plant. (2012).

[6] Danish Energy Authority (In Danish: Energistyrelsen), Assumptions for economic analyses in the energy sector (Danish: Forudsætninger for samfundsøkonomiske analyser på energiområdet) (2011).

[7] Danish Energy Authority, Energinet.dk, Technology Data for Energy Plants - Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion (2012).

[8] S. Rudra, Design and system analysis of quad-generation plant based on biomass gasification integrated with district heating (2013).

[9] M.B. Blarke, H. Lund, The effectiveness of storage and relocation options in renewable energy systems, Renewable Energy. 33 (2008) 1499-1507.

[10] M.B. Blarke, Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration, Appl. Energy. 91 (2012) 349-365.

[11] J. Møller Jensen, J.J. Møller, Design reference year DRY (In Danish: Et nyt dansk referenceår) (1995).

[12] NASDAQ OMX Commodities Europe, Prices as of March 27th 2013: Carbon EUA €5/ton, Carbon CER €0,35 http://www.nasdaqomx.com/commodities. 30-03-2013.

[13] M.B. Blarke, B.M. Jenkins, SuperGrid or SmartGrid: Competing strategies for large-scale integration of intermittent renewables?, Energy Policy. 58 (2013) 381-390.

[14] M.B. Blarke, S. Rudra, L. Rosendahl, QUAD-Generation: Techno-Economic Analysis Of A 100% Renewable Energy Plant For Flexible Local Production Of Electricity, Heating, Cooling, And FuelsThird International 100% Renewable Energy Conference (IRENEC2013), Istanbul, Turkey, June 27-29, 2013 (2013).