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Polygeneration of Fuels and Chemicals

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Abstract

Research advances in the rapidly growing field of polygeneration are highlighted. Although "polygeneration" has had many meanings, the chemical engineering community has overwhelmingly settled on a meaning which describes a process that co-produces at least two products: electricity, and at least one chemical or fuel via a thermochemical route that does not rely on petroleum. The production of syngas is almost always the primary intermediate for energy conversion, but the feeds, products, technologies, and pathways vary widely. However, the choice of the most optimal polygeneration system is highly dependent on circumstance, and often results in systems with only one fuel or chemical co-produced with electricity. Conversely, the synergistic use of multiple types of feedstocks can have important profitability benefits.

Introduction

In polygeneration, several different kinds of chemical processes are tightly integrated together into one larger process. By doing this, certain synergies can be exploited which makes the resulting process more efficient, more economical, and/or more environmentally friendly than independent, stand-alone processes. For example, in the production of chemicals such as methanol from syngas, there are often waste gases of which only some can be recycled to synthesis reactors and the rest must be purged. For a standalone methanol plant, it makes sense to have very high recycle rates in order to maximize the production of its only product. However, because recycling has diminishing returns, it may make more economic sense to simply recycle less (or nothing!) and instead use the waste gases for electricity production, thus resulting in a plant which co-produces methanol and a net surplus of electricity in large quantities. Or, if a company has a need for several particular different kinds of chemicals or fuels, a polygeneration process which uses the same supply of syngas (a blend of carbon monoxide and hydrogen) to produce all of the chemical or fuel products may make economic sense because the syngas generation steps required for the various products can be integrated all into one. Whatever the case, the idea is to gain some advantage by the integration of the different process sections.

Terminology and Scope

The word "polygeneration" is very broad since many kinds of processes can produce more than one product simultaneously (e.g. petroleum refining). Although the idea of co-producing multiple products had been understood for some time, the term "polygeneration" first appears in the open engineering literature in 1982 (to the best of the authors' knowledge) through studies at NASA [1] and General Electric [2]. Although those works and almost all other early works focused on the systems using only coal gasification, researchers now use the term more broadly to apply to systems which use natural gas, biomass, and nuclear energy. Of all academic literature using the term "polygeneration" (that could be identified) published between January 2013 and April 2015 [4-45,51-52], none apply it with respect to crude oil, and in every case in which the term is used except one [26], electricity is a co-product.

Two seminal works from 1982 represent the genesis of two different meanings of the term developed over the past three decades. The NASA usage [1] helped lead to an understanding of the term in the context of two or more co-products in total where one is a chemical or fuel. The General Electric usage [2] helped lead to an understanding of the term in the context of municipal utilities, where polygeneration is the natural extension of well-understood terms such as "co-generation" (electricity and heat), and "tri-generation" (electricity, heat, and cooling). In the latter context, polygeneration typically means a tri-generation system with more utility products such as drinking water, or secondary forms of heat or cold (e.g. steam, refrigeration, air conditioning, etc.). However, the former definition has won over. All works that the authors can identify in the engineering literature which use the term "polygeneration" since 2013 includes at least one chemical or fuel as a co-product in addition to electricity, except for the works of a few research groups [22, 29, 33, 54]. In addition, all research groups except one [10,21] apply the term to a thermochemical process as opposed to a biochemical one. This represents a shift in the cultural use of "polygeneration" strongly in favour of the former meaning. Therefore, based on the overwhelming consensus of the terminology in the literature, the authors propose the following definitions for use in a chemical engineering context:

- **Co-generation**: A process with electricity and heat (usually in the form of either steam or hot water) as products. Also called “combined heat and power.”
- **Tri-generation:** A process with electricity, heat (usually in the form of either hot water or steam), and cooling (such as air conditioning services or chilled water) as products.
- **Polygeneration:** A thermochemical process which simultaneously produces at least two different products in non-trivial quantities, but is not a petroleum refining process, a co-generation process, or a tri-generation process, and at least one product is a chemical or fuel, and at least one is electricity.

The term also overlaps with the term “biorefinery”, which can be explained as follows:

- **Biorefinery:** A process for converting biomass into value-added products, including electricity, fuels, chemicals, food, and proteins. This can include thermochemical routes such as gasification, or biochemical routes such as fermentation or digestion. See [3] for a review of the term.
- **Thermochemical Biorefinery:** A process which is both a polygeneration process and a biorefinery (thus via the thermochemical route).

As a final note, the scope of this review was limited to processes which self-identify as “polygeneration”. The reader is referred to [48, 49] for recent reviews of biorefineries, which include thermochemical biorefineries and hence, polygeneration.

The Syngas Route

In almost all studies examined in this work, polygeneration utilizes the “syngas route,” as summarized in Table 1. The general strategy is to first produce syngas of some variety, usually containing a mix of H_2 and CO (the valuable parts), along with wastes such as CO_2 and H_2O (arising through oxidation of fuels), and impurities such as sulphurous compounds. The syngas has to then be modified to balance the molar ratio of H_2 to CO to some optimum value, based on the stoichiometry of the reaction. Typically, slightly more than twice as much H_2 as CO is optimal for most downstream fuel and chemical conversion processes, such as Fischer-Tropsch synthesis, or methanol synthesis. In some cases, an equimolar ratio is optimal, such as in the case of direct DME conversion. Additionally, the syngas must be cleaned to remove CO_2, H_2O, and impurities that may harm catalysts or cause problematic emissions or inefficiencies. However, the order of these steps varies from process to process. Once the clean, "balanced," syngas is produced, it can be split and fed to several different synthesis trains in parallel, since they often require very similar syngas compositions. Often, a portion of the unreacted syngas is recycled to the synthesis reactor, depending on the economics of the process. However, nearly always, the remaining off-gas is sent to power generation since syngas has a high heating value, even when it contains a large amount of diluents like H_2O and CO_2. The result is often a large net-excess of power produced arising from this configuration.

Syngas Production and Balancing

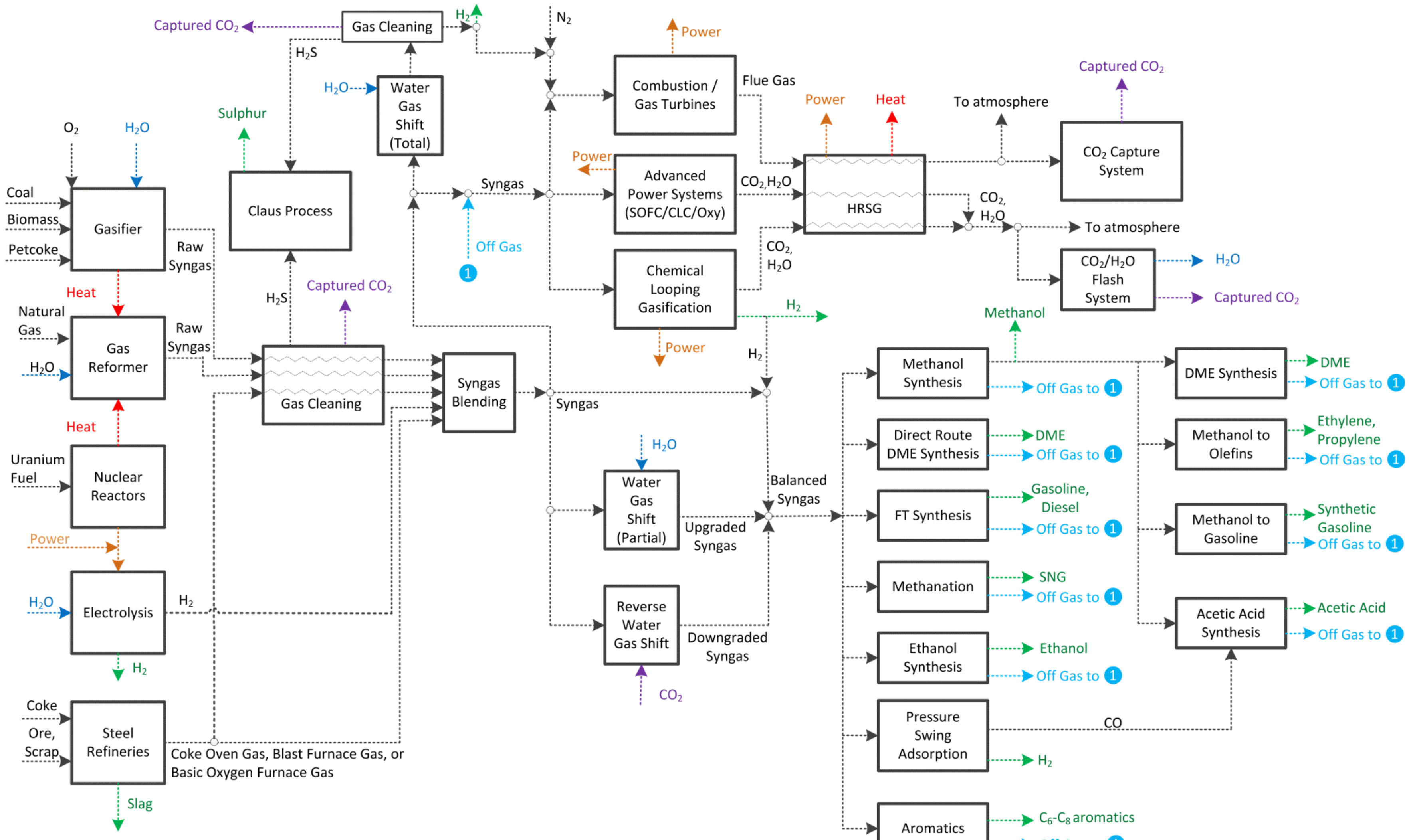
On key characteristic that distinguishes a polygeneration process is the manner in which "balanced" syngas is produced. Figure 1 outlines a polygeneration superstructure of all processes surveyed in this work. Each box in this figure is optional to some degree, as is many of the feed streams, stream splits, recycle, or stream merges. There are many levels of detail inside each of the boxes which are not shown for simplicity, and not all interconnections between them are shown either. However, the general strategies are prevalent.

Coal and biomass can be converted to syngas through gasification technologies, of which there are many different types. In most cases, this requires the use of high-purity O_2 produced by an air separation process, which is expensive, energy intensive, and a major source of inefficiency. Typically, this produces "H_2-lean" syngas, meaning that the syngas needs to be upgraded to a higher H_2 content suitable to the desired downstream molar ratio. Common strategies for this include using a water gas shift reactor, blending in high purity H_2 produced by some other means, or blending in "H_2-rich" syngas which has a high H_2/CO molar ratio, such that the blended mix has the desired balance. Each method has its own special challenges and trade-offs.

Table 1: Summary of works in the review period and scope classified as polygeneration by the authors, with feedstock type and product portfolio noted.

		Feedstocks					Products									
Authors	**Refs**	**Coal**	**Nat. Gas**	**Biomass**	**Nuclear**	**Other**	**Electricty**	**FT Fuels**	**Alcohols**	**Olefins**	**DME**	**H2**	**SNG**	**Heat**	**Other**	**Notes**
Fan & Lin	[4]		X				X					X				
Ghanbari et al.	[5] [43]	X	X	X		steel off gases	X		X		X					
Guo et al.	[6]					lignite	X								tar	Does not use the syngas route
Guo et al.	[18]	X					X		X							
Heidenreich & Foscolo	[7]			X			X					X	X	X		
Jana & De	[8] [9]			X			X		X					X	cooling	
Vidal & Martín	[11]			X			X					X				Concentrated solar thermal
Wagner et al.	[12]			X			X						X	X		
Khojestah Salkuyeh & Adams	[13][51]		X				X		X	X	X					
Khojestah Salkuyeh & Adams	[15]	X	X		X		X		X		X					Chemical looping
Khojestah Salkuyeh & Adams	[37]	X	X		X		X	X								
Carvalho et al.	[16]			X			X	X						X	X	
Zhang X et al.	[17]	X	X				X		X							Chemical looping
Li S et al.	[20][35]	X					X						X			
Illic et al.	[19]		X				X	X	X					X		
Cormos	[23]			X			X					X				Chemical looping
Cormos	[27]	X		X			X	X				X	X			
Ruth et al.	[24]	X	X	X	X	wind	X	X	X	X		X				Subsets of these considered
Li Y et al.	[25]	X					X		X							
Navarez et al.	[42]					syngas	X		X							
Zhang J et al.	[44]	X					X		X							
Yi et al.	[52]	X				coke oven gas	X		X							
Fazlollahi & Maréchal	[28]			X			X						X	X		
James et. Al	[30]	X		X			X	X								
Kaniyal et al.	[31][32]	X	X	X			X	X								Solar+co-gasification/reforming
Kyriakarakos et al.	[34]					electricity	X					X		X	cooling	Elec. both resource & product
Ng et al.	[36]	X	X	X			X	X				X	X		acetic acid	
Salomón et al.	[38]			X			X	X						X		
Truong & Gustavsson	[39]			X			X	X						X	bio-pellets	
He et al.	[53]	X		X			X	X								Low rank coal

Figure 1. Polygeneration superstructure of works in the review period and scope which use the syngas route. Many blocks, streams, and routes are optional. SOFC=Solid oxide fuel cells, CLC=chemical looping combustion, OXY=oxyfuel



Syngas can also be produced by the reforming of natural gas, of which many strategies are possible. Gas reforming strategies differ mostly in the amounts of steam, CO_2, and O_2 which are fed (not all are required), the types of catalyst used, and how heat is supplied since the reforming reactions are quite endothermic. This allows the system designer much control over the H_2/CO ratio produced. For example, it may make sense to either directly produce the appropriate H_2/CO ratio (i.e. of about two) in the reformer, or alternatively produce an H_2-rich syngas that can either be blended with something else, or downgraded using a reverse water gas shift reactor. The heat requirement can be provided by placing the reformer in a furnace, direct oxidation inside the reactor, or by integrating with something highly exothermic such as a coal gasifier or a nuclear reactor (see "Multi-feed processes").

Offgas Usage, Power Generation, and CO_2 Emissions

Once balanced syngas is used for chemical or fuel production, there usually remains a substantial amount of off-gases. These off gases exist because of purge requirements necessary to prevent build-up of CO_2 and H_2O. When the expense of removing CO_2 and H_2O to permit recycling is too great, the off gas is typically used for either power generation or burned for heat. There are many power generation options, such as classic combustion with a steam cycle, the more advanced gas combustion turbine with combined cycle, or more futuristic options such as solid oxide fuel cells, oxyfuel combustion, and chemical looping combustion. These power generation options vary in terms of cost, efficiency, and the relative difficulty of capturing CO_2, but all of them can be designed (in theory) to handle off-gas compositions of widely differing amounts, which make them universally attractive as the best and most profitable way to use off-gases. The latter three options in particular are prevalent because they each have the ability to effectively capture up to 100% of the CO_2. This means that some polygeneration systems can be designed such that all of the carbon in the feed ends up in either the products, or, the captured CO_2, leading to systems with effectively zero process CO_2 emissions [13, 14, 15,]. Even if carbon capture is not employed, CO_2 emissions can still be reduced compared to stand-alone alternatives simply due to efficiency improvements as a result of system integration, which was repeatedly demonstrated in the literature surveyed [5, 17, 43, 51, 53]. For more on this topic, the reader is referred to [46].

Multi-feed processes

Another common approach is to utilize multiple feedstocks together to gain some sort of synergy, which are sometimes referred to as hybrid energy systems (see [47] for a review prior to 2012). Some synergy may be found in the blending of H_2-lean syngas with H_2-rich syngas. This can avoid losses associated with the water gas shift reaction necessary to upgrade coal-derived syngas [17], or avoid losses associated with dry reforming or the reverse water gas shift reaction necessary to downgrade syngas made from natural gas. Or, synergy can be found through heat integration, such as using the high temperatures produced by coal gasification or nuclear reactors to drive natural gas reforming processes, which can simultaneously avoid gas burning for heat or steam production for cooling (which has a lower exergy benefit than reforming natural gas) [17,37].

Alternatively, it may make sense to blend fuels purely for their superior environmental qualities. For example, a company might try to “green up” a coal-based process by also using large amounts of natural gas or biomass, thus lowering the lifecycle CO_2 emissions as a whole or increasing the use of renewable fuels [5, 53]. Similarly, a polygeneration process can be a means to utilize or dispose of low value feeds like municipal solid waste or petroleum coke by blending it in with coal or integrating with a natural gas reforming route. In some cases, blending in non-trivial amounts of waste might result in only a relatively small negative impact on the system [27], thus providing a very effective and efficient means of disposal by conversion to new products.

Optimal Design of Polygeneration Systems

In much of the literature surveyed, the determination of an “optimal” polygeneration system was studied, which often took the form of finding the optimal design parameters (such as recycle amounts of unreacted-gases or off-gases), for a given design concept. Or, the optimization of a polygeneration superstructure was considered, by which the best subset of many candidate routes and products was determined (see [50] for a recent example).

The optimal results are often highly dependent on market conditions, but also tend to favour two-product systems. For example, if the objective is simply to make the most profitable plant (e.g. the highest net present value) with no attachment to a particular product, it is very often the case that the optimal process co-produces electricity and the choice of only one chemical or fuel. This is because there is very little synergy between the chemical and fuel synthesis trains themselves. For example, it rarely makes sense to make both methanol and dimethyl ether (DME) when DME is produced from methanol dehydration. Either the price of DME is not higher enough than methanol to justify the cost of methanol dehydration and so the dehydration step should not exist, or, the price difference is high enough such that you should build a methanol dehydration reactor and therefore any methanol produced should be used to produce DME. Similarly, it is rarely the case in which the optimal system design is one in which syngas is split between two separate chemical or fuel synthesis trains, such as a Fischer-Tropsch train and a methanol synthesis train; typically syngas should all be routed to just one[†]. In fact, sometimes the most desirable design is simply a single product plant, and not a polygeneration system at all.

The exceptions to this result tend to be cases in which constraints or objectives outside of pure profitability are considered. For example, if there is a market for it, there can often be a way to sell low-quality heat in the form of low pressure steam or hot water. Or, if there are broader goals such as requiring certain minimum production rates of various products, or a desire to produce a portfolio of products in the same proportion as the global demand. Similarly, some of the works in the survey noted that polygeneration may lower the overall production costs of producing some required “chemical X” by capturing value associated with the co-products of polygeneration. However, in some cases this is because it simply is more profitable to make the co-products than the primary product of interest, and the lower production costs of chemical X are mostly the result of accounting style rather than of any meaningful synergies arising from the integration of the co-processes. In those cases, polygeneration is not likely to be much of a help, unless the production of chemical X is required regardless of cost.

However, it is often the opposite when considering multiple types of feeds. Because of the synergies that are inherent in the use of multiple feeds (see previous section), there are many cases in those surveyed in which it was optimal to use multiple types of feeds from a purely profit driven perspective. For example, under certain carbon taxes, blending a certain percentage of biomass into

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[†] Of course, an individual train may by necessity co-produce a basket of related products, such as Fischer-Tropsch diesel and naphtha, but the point still holds.

coal for gasification may be the best overall strategy; using no biomass (all coal) would require heavy CO_2 tax or capture expense penalties, but using too much would have too many negative impacts on the system such that the overall efficiency and profitably drops too far. Or, the avoidance of syngas upgrading or downgrading by blending coal-derived syngas with syngas made from natural gas may have enough efficiency improvements to have a net positive impact on profitability compared to any single-feed system.

Conclusions and Future Directions

Polygeneration systems research is growing rapidly because the core concepts of synergistic process integration can be applied to a wide variety of systems and applications, including some newer examples in the steel and mining industries. The key benefits can include higher profitability, better efficiency, and lower environmental impact, although the choice of the "best" design is highly dependent on particular business, regulatory, or market circumstances. Because market conditions (which can be highly variable) greatly affect the optimal process topologies, it makes sense to pay closer attention to flexible polygeneration systems which change the relative amounts of each product produced or feedstock used periodically (yearly, seasonally, weekly, or even daily) in order to respond to these changes and make more profit than a static, unchanging plant would. This may be the most promising use for polygeneration since the general system structure is favourable, provided that it is designed for excess capacity and enough turndown capability is possible.

Acknowledgements

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest

** of outstanding interest

1. Burns RK, Staiger PJ, Donovan RM. **Integrated gasifier combined cycle polygeneration system to produce liquid hydrogen. *NASA Technical Memorandum*, Report No NASA TM-82921, July 1982

This is the first engineering article to use the term polygeneration, and it demonstrated to excellent detail that one coal-based polygeneration system requires lower energy consumption than a collection of standalone facilities (11-13% in this case), along with potential economic benefits as well.

2. Alger J, Ahner DJ. **Cool water demonstration project and its industrial applications**. *Proc., Interso. Energy Convers Eng Conf* 1982, 1:17

3. Berntsson T, Sandén B, Olsson L, Åsblad A. **What is a biorefinery?** In: Systems Perspectives on Biorefineries. Sandén B, Pettersson, K, eds. 2014. Chalmers University of Technology.

4. Fan J, Lin Z. **Performance analysis of a feasible technology for power and high-purity hydrogen production driven by methane fuel**. *App Thermal Eng* 2015 75:103-114.

5. Ghanbari H, Pettersson F, Saxén H. **Sustainable development of primary steelmaking under novel blast furnace operation and injection of different reducing agents. *Chem Eng Sci* 2015, 129:208-22.

This is interesting in that it specifically links polygeneration with steel manufacturing to co-produce steel products with methanol and/or DME. A large polygeneration superstructure and many possible fuel sources are considered by making syngas from coke plant, blast furnace and basic oxygen furnace residual gases. A follow-up article from [43].

6. Guo Z, Wang Q, Fang M, Luo Z, Cen K**. Simulation of a lignite-based polygeneration system coproducting electricity and tar with carbon capture**. *Chem Eng Technol* 2015, 38:463-472.

*7. Heidenreich S, Foscolo PU. **New concepts in biomass gasification**. *Prog Energy Combust Sci* 2015, 46:72-95.

Contains a review of different ways of producing syngas for polygeneration from biomass, including some interesting unconventional designs which incorporate gasification, cleaning, and conditioning in one reactor.

8. Jana K, De S. **Polygeneration using agricultural waste: Thermodynamic and economic feasibility study**. *Renew Energy* 2015,74:648-660.

9. Jana K, De S. **Techno-economic evaluation of a polygeneration using agricultural residue – A case study for an Indian district**. *Bioresource Technol* 2015, 181:163-173.

*10. Lythcke-Jørgensen C, Haglind F. Design optimization of a polygeneration plant producing power, **heat, and lignocellulosic ethanol.** *Energy Convers Manage* 2015,91:353-366.
Based on retrofitting an existing co-generation plant, this high quality work is notable for considering flexible production on an hour by hour basis. It uses simultaneous saccharification and fermentation to produce ethanol and is not classified as polygeneration under the definition put forward in this work.

*11. Vidal M, Martín M. **Optimal coupling of a biomass based polygeneration system with a concentrated solar power facility for the constant production of electricity over a year.** *Comp Chem Eng* 2015,72:273-283.
This work is notable for the integration of flexible polygeneration with concentrated solar thermal energy with molten salt energy storage. The molten salts handle daily energy storage issues while hydrogen is produced at different amounts each month based on seasonal variations in average sunlight.

*12. Wagner H, Wulf C, Kaltschmitt M. **Polygeneration of SNG, heat and power based on biomass gasification and water electrolysis—concepts and their assessment.** *Biomass Conv Bioref* 2015,5:103-114.
This process either produces or consumes power depending on prices; when power is low, electrolysis is purchased to produce hydrogen for energy storage purposes.

13. Khojestah Salkuyeh Y, Adams TA II. **Co-production of olefins, fuels, and electricity from conventional pipeline gas and shale gas with near-zero CO_2 emissions**. **Part II: Economic performance**. *Energies* 2015, 8:3762-3774.

The optimization results of this paper show that unless market prices for chemicals and fuels are in a very particular and narrow range, the most profitable polygeneration plants are those that co-produce electricity with only one of the possible products considered (dimethyl ether, olefins, or methanol). It rarely makes sense to co-produce two kinds of chemicals due to the lack of synergies between their process trains.

14. Khojestah Salkuyeh Y, Adams TA II. **A novel polygeneration process to co-produce ethylene and electricity from shale gas with zero CO_2 emissions via methane oxidative coupling.** *Energy Convers Manage* 2015, 92:406-420.

*15. Khojestah Salkuyeh Y, Adams TA II. **A new power, methanol, and DME polygeneration process using integrated chemical looping systems.** *Energy Convers Manage* 2014, 88:411-425.

This work considers coal-only and coal/natural gas co-feeds in different proportions, and under current market conditions, using both coal and natural gas are the most profitable. Also, heat from a nuclear reactor can be used to power natural gas reforming to reduce fossil fuel consumption associated with heat production and improve the efficiency.

16. Carvalho M, Romero A, Shields G, Millar DL. **Optimal synthesis of energy supply systems for remote open pit mines. *App Thermal Eng* 2014,64:315-330.

This excellent work solves MILP polygeneration superstructure optimization problems to find the best solutions for a remote mining operation, noting monthly and hourly variability in demands for heat, diesel, and power. It is particularly interesting because in this case there are limits to the capacity of power grid that can be reached and the optimal energy storage (such as syngas storage) and power management systems change drastically with the distance to the connection point.

*17. Zhang X, Li S, Jin H. **A polygeneration system based on multi-input chemical looping combustion**. *Energies* 2014, 7:7166-7177.

Combines coal and natural gas to co-produce methanol and electricity. This shows that using natural gas to upgrade H_2-lean coal-derived syngas instead of the water gas shift reaction is more efficient and has lower exergy destruction.

18. Guo Z, Wang Q, Fang M, Luo Z, Cen K. **Thermodynamic and economic analysis of a polygeneration systems integrating atmospheric pressure coal pyrolysis technology with circulating fluidized bed power plant**. *App Energy* 2014, 113:1301-1314.

19. Ilic DD, Dotzauer E, Trygg L, Broman G. **Introduction of large-scale biofuel production in a district heating system-an opportunity for reduction of global greenhouse gas emissions**. *J Cleaner Prod* 2014, 64:552-561.

20. Li S, Jin H, Gao L, Zhang X. **Exergy analysis and the energy saving mechanism for coal to synthetic/substitute natural gas and power cogeneration system without and with CO_2 capture**. *App Energy* 2014, 130:552-561.

21. Lythcke-Jørgensen C, Haglind F. **Design optimization of a polygeneration plant producing power, heat, and lignocellulosic ethanol**. *Energy Convers Manage* 2014, 91:353-366.

22. Kasivisvanathan H, Ubando AT, Ng DKS, Tan RR. **Robust optimization for process synthesis and design of multifunctional energy systems with uncertainties**. *Ind Eng Chem Res* 2014 53:3196-3209.

23. Cormos CC. **Biomass direct chemical looping for hydrogen and power co-production: Process configuration, simulation, thermal integration and techno-economic assessment.** *Fuel Process Technol* 2015, 137:16-23.

*24. Ruth MF, Zinaman OR, Antkowiak M, Boardman RD, Cherry RS, Bazilian MD. **Nuclear-renewable hybrid energy systems: Opportunities, interconnections, and needs**. *Energy Convers Manage* 2014 78:684-694.

This work provides an overview into the various ways in which nuclear energy can be integrated into polygeneration systems, such as providing the heat for natural gas reforming needs.

25. Li Y, Zhang G, Yang Y, Zhai D, Zhang K, Xu G. **Thermodynamic analysis of a coal-based polygeneration system with partial gasification**. *Energy* 2014, 72:201-214.

26. Brau J-F, Morandin M, Berntsson T. **Hydrogen for oil refining via biomass indirect steam gasification: energy and environmental targets.** *Clean Techn Environ Policy* 2013, 15:501-512.

*27. Cormos C-C. **Assessment of flexible energy vectors polygeneration based on coal and biomass/solid wastes co-gasification with carbon capture**. *Int J Hydrogen Energy* 2013, 38:7855-7866.

This work proposes blending low value feedstocks (such as municipal solid waste) with coal for gasification such the net negative effects on the system (compared to coal-only) are small.

28. Fazlollahi S, Maréchal F. **Multi-objective, multi-period optimization of biomass conversion technologies using evolutionary algorithms and mixed integer linear programming (MILP).** *App Thermal Eng* 2013, 50: 1504-1513.

29. Hossain AK, Thorpe R, Vasudevan P, Sen PK, Citroph RE, Davies PA. **Omnigen: Providing electricity, food preparation, cold storage and pure water using a variety of local fuels**. *Renewable Energy* 2013, 49:197-202.

30. James OO, Chowdhury B, Auroux A, Maity S. **Low CO_2 selective iron based Fischer–Tropsch catalysts for coal based polygeneration**. *Applied Energy* 2013, 107:377-383.

31. Kaniyal AA, van Eyk PJ, Nathan G, Ashman PJ, Pincus JJ. **Polygeneration of Liquid Fuels and Electricity by the Atmospheric Pressure Hybrid Solar Gasification of Coal**. *Energy Fuels* 2013, 27:3538-3555.

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33. Kasivisvanathan H, Bariela IDU, Ng DKS, Tan RR. **Optimal operational adjustment in multi-functional energy systems in response to process inoperability**. *Applied Energy* 2013, 102: 492-500.

*34. Kyriakarakos G, Piromalis DD, Dounis AI, Arvanitis KG, Papadakis G. **Intelligent demand side energy management system for autonomous polygeneration microgrids.** *Applied Energy* 2013, 103:39-51.

This work provides a framework for optimal design and operation of autonomous, small polygeneration systems for microgrids, considering flexible operation and load-following aspects.

35. Li S, Jin H, Gao L. **Cogeneration of substitute natural gas and power from coal by moderate recycle of the chemical unconverted gas**. *Energy* 2013, 55: 658-667.

*36. Ng KS, Zhang N, Sadhukhan J. **Techno-economic analysis of polygeneration systems with carbon capture and storage and CO_2 reuse**. *Chem Eng J* 2013, 219:96-108.

This work looks at a number of interesting configurations using a variety of fuels and products, including a unique way of using combining gas-derived and coal-derived syngas.

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38. Salomón M, Gomez MF, Martin A. **Technical polygeneration potential in palm oil mills in Columbia: A case study**. *Sustain Energy Technol Assess* 2013, 3:40-52.

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