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(54) **POLYGENERATION SYSTEMS**

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(57) **ABSTRACT**

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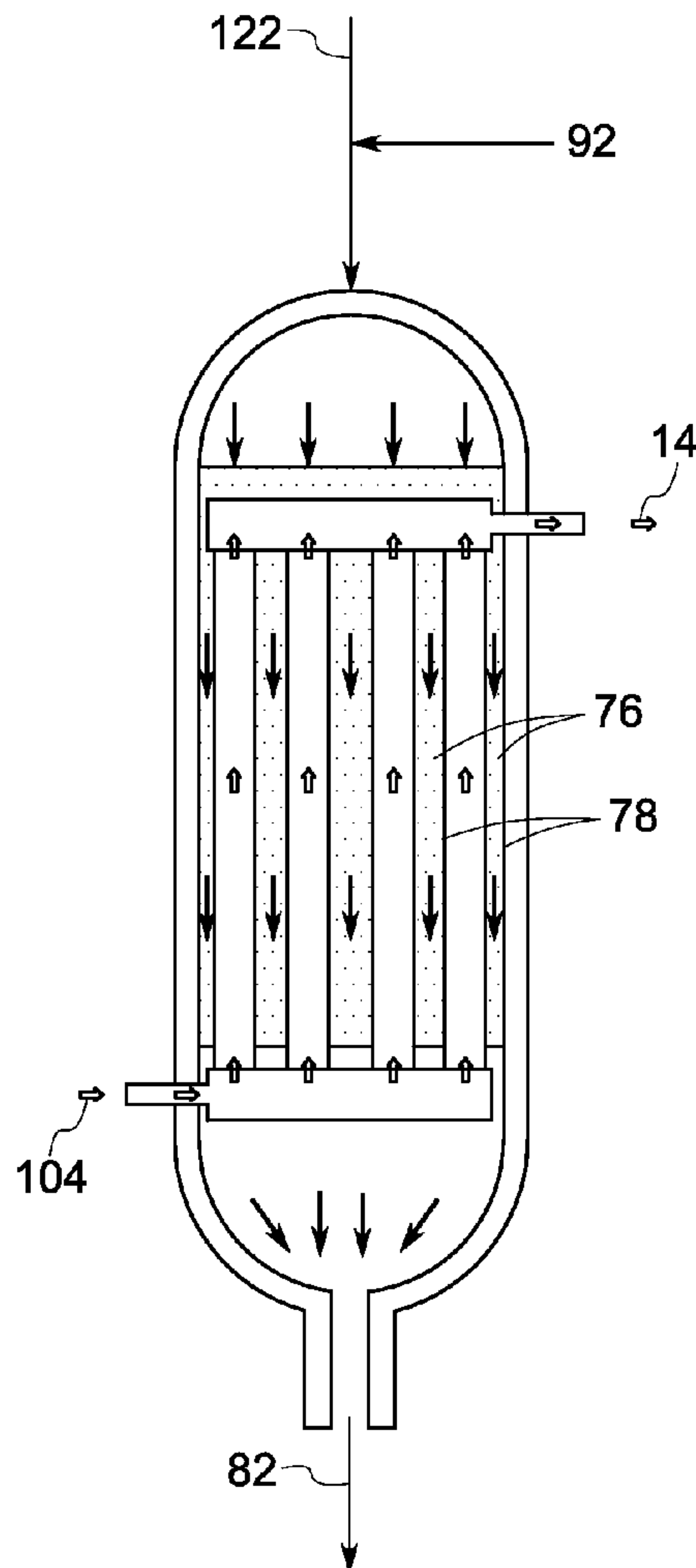
A polygeneration system, wherein the various units of the polygeneration system are integrated to effectively separate the undesired species. In one embodiment, a polygeneration system is provided that includes a syngas generator for producing a syngas, a syngas enrichment unit for separating undesired species from the syngas to produce an enriched syngas and a syngas utilization system that utilizes the enriched syngas to produce useful products and a stream to facilitate the separation of undesired species in the syngas enrichment unit. In some embodiments, the polygeneration system includes membrane reactor, catalytic burner and power generation unit.

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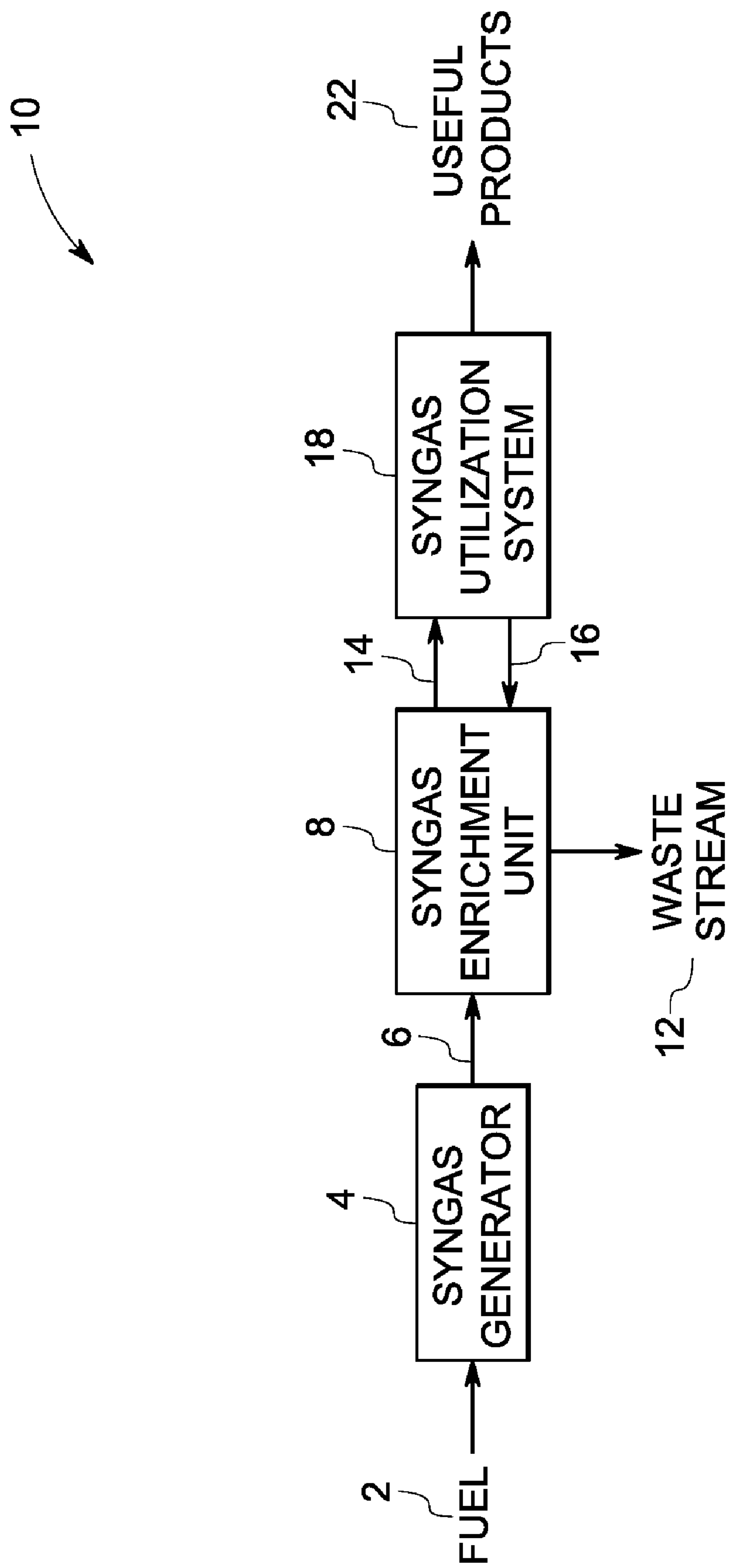


FIG. 1

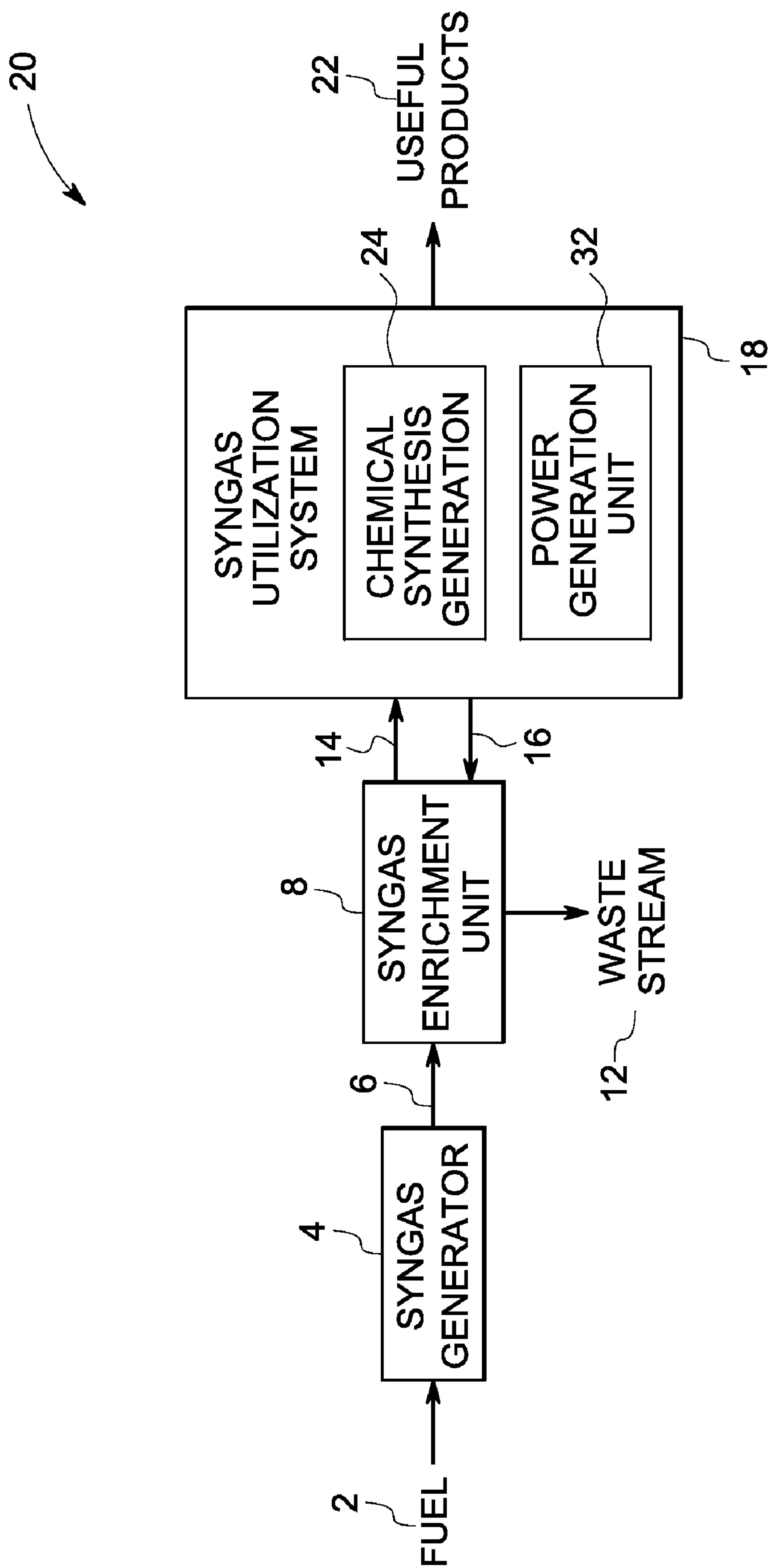


FIG. 2

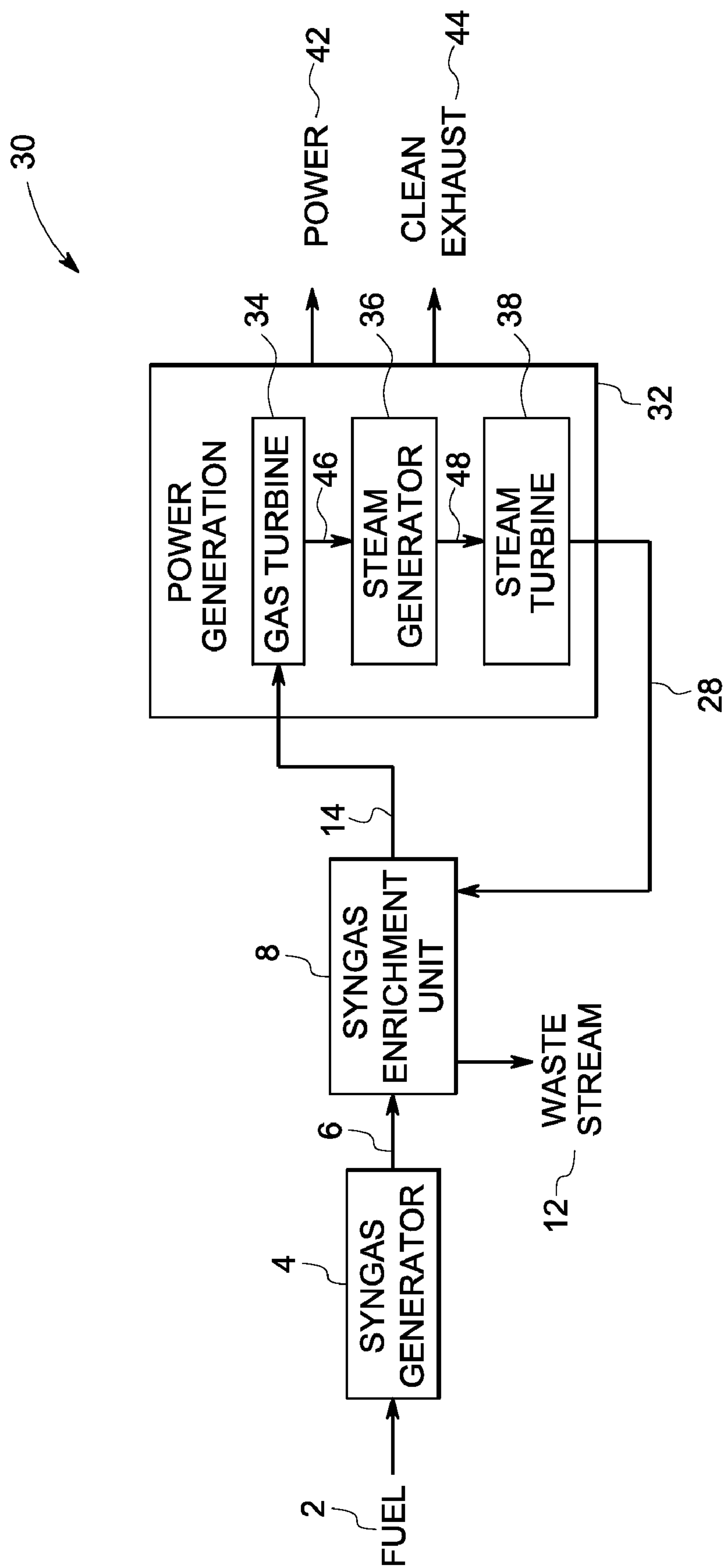


FIG. 3

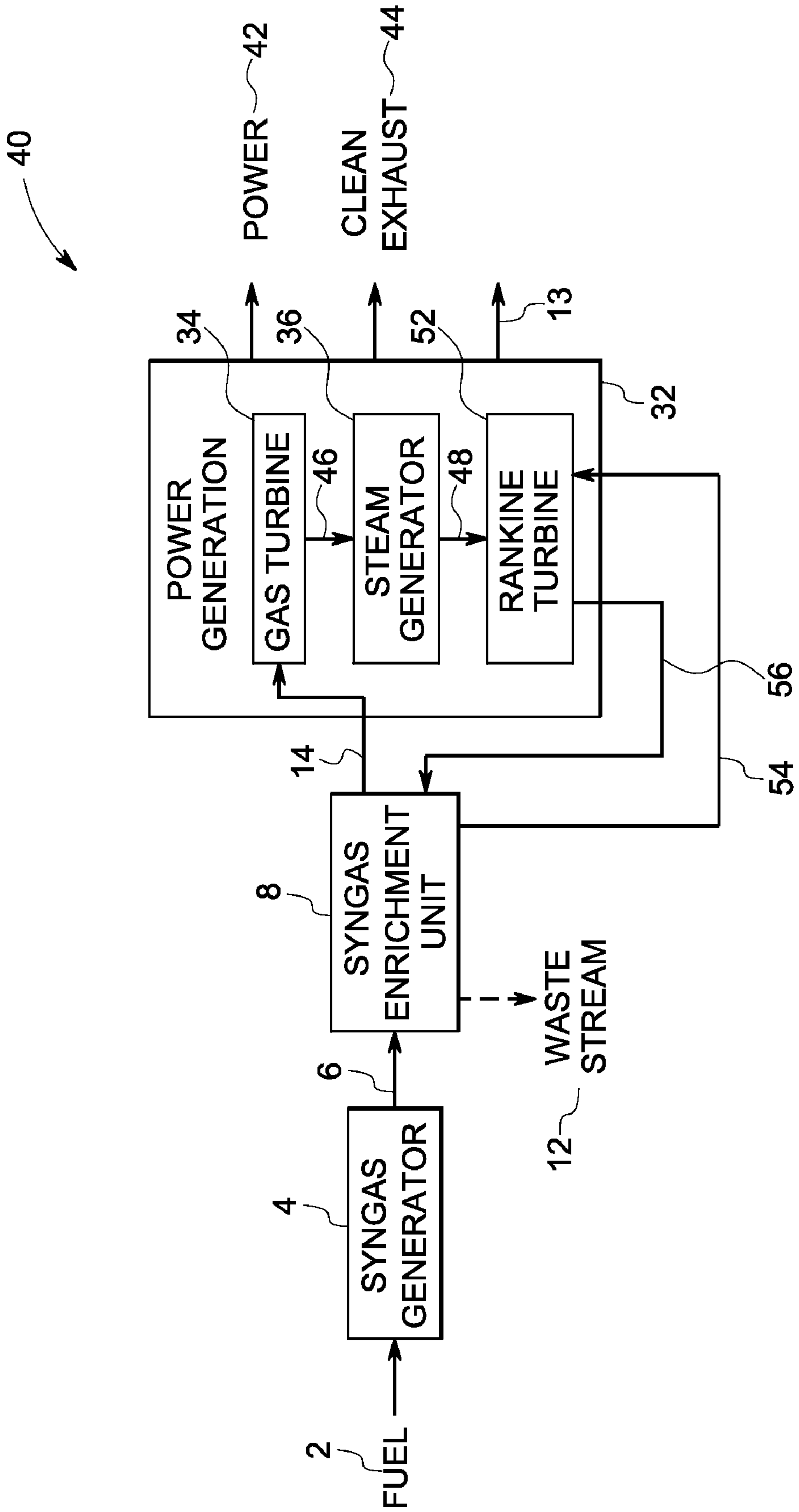


FIG. 4

50

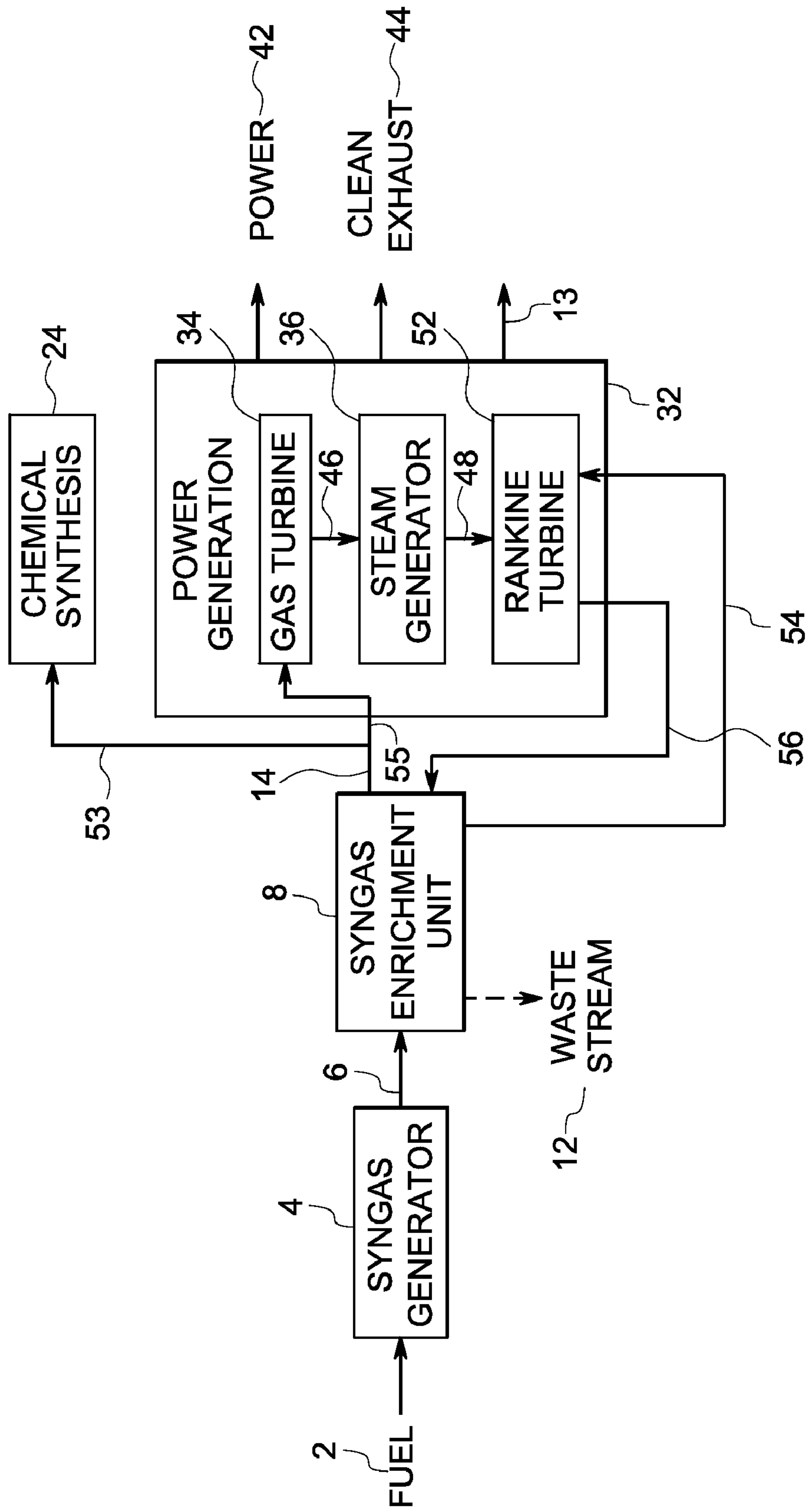


FIG. 5

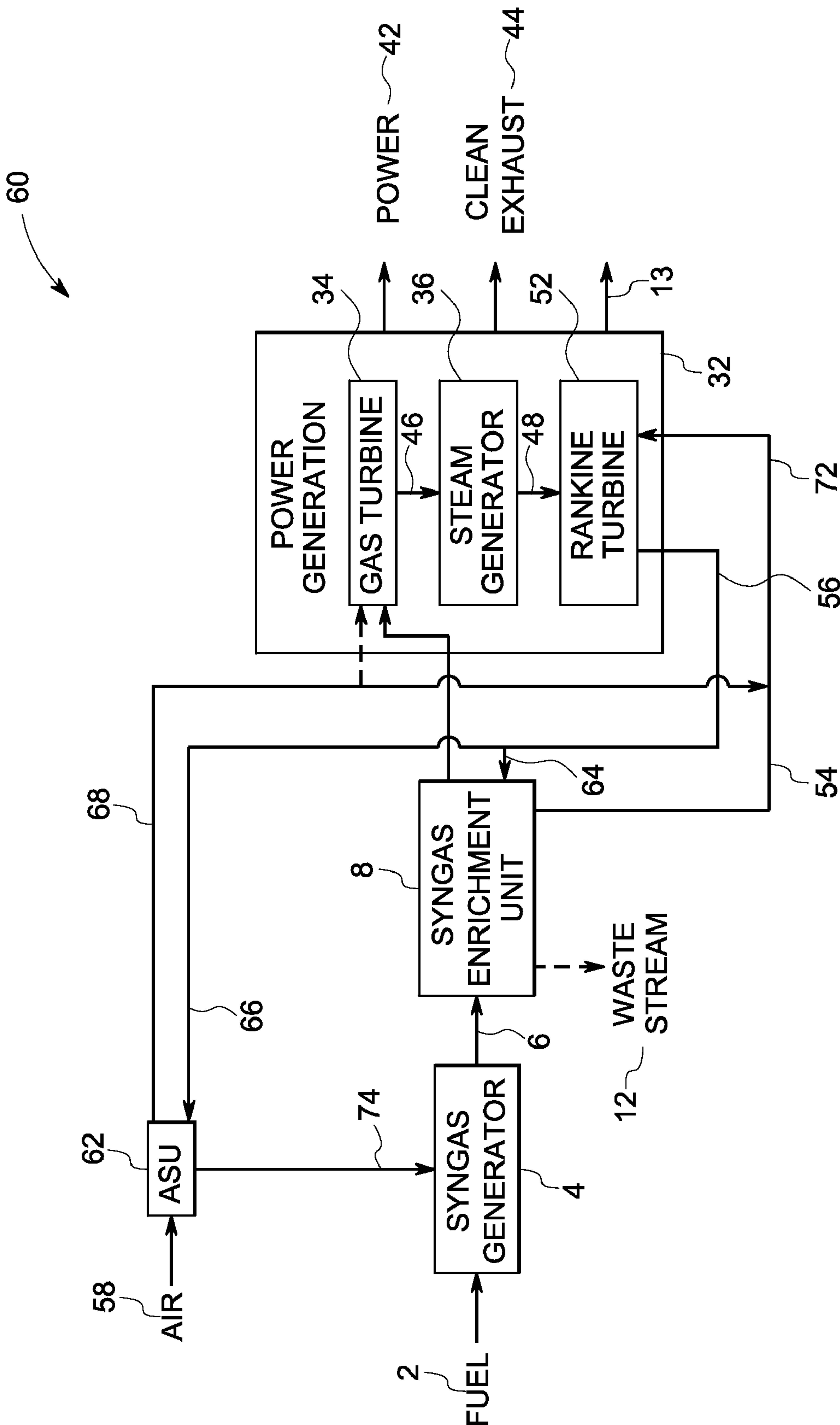


FIG. 6

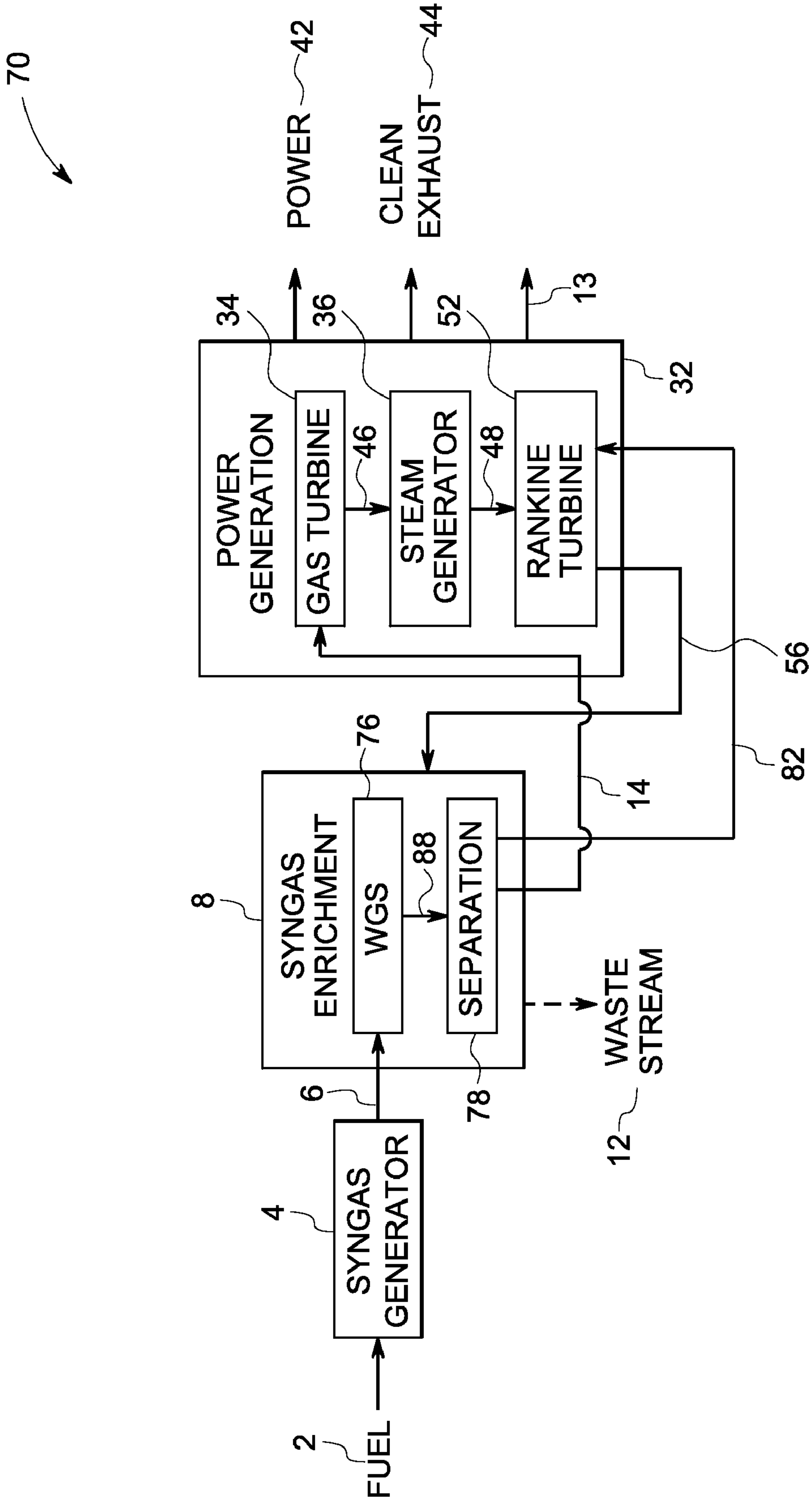


FIG. 7

80

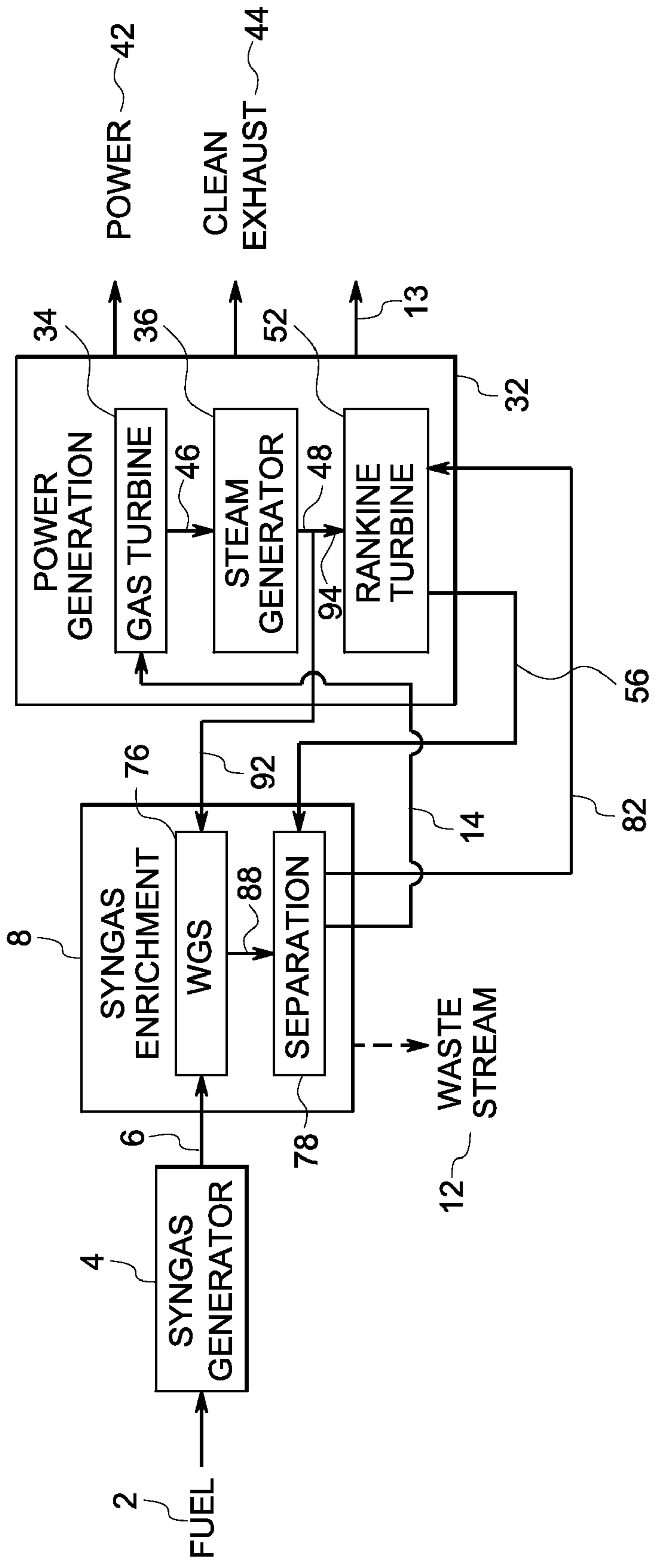


FIG. 8

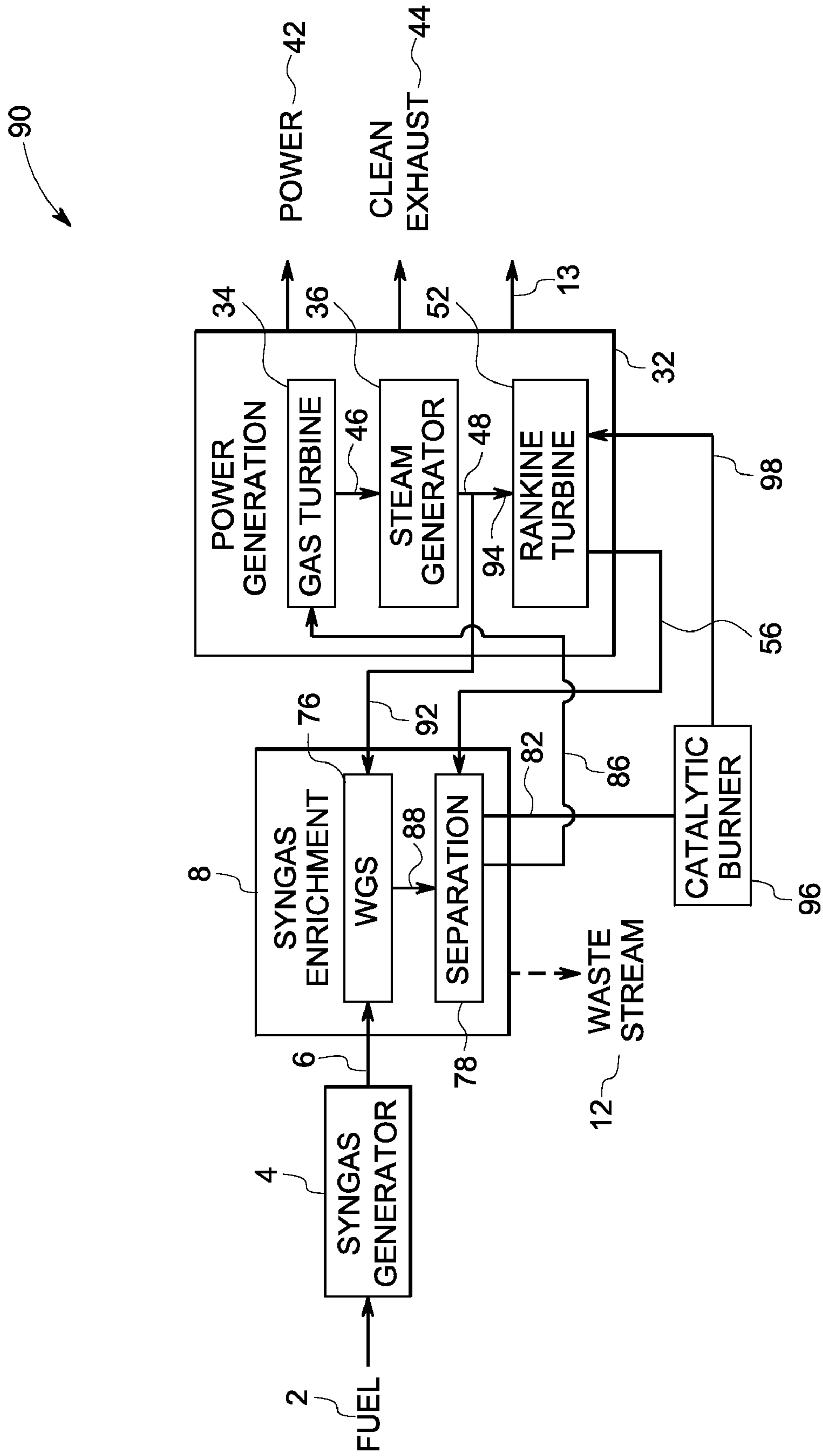


FIG. 9

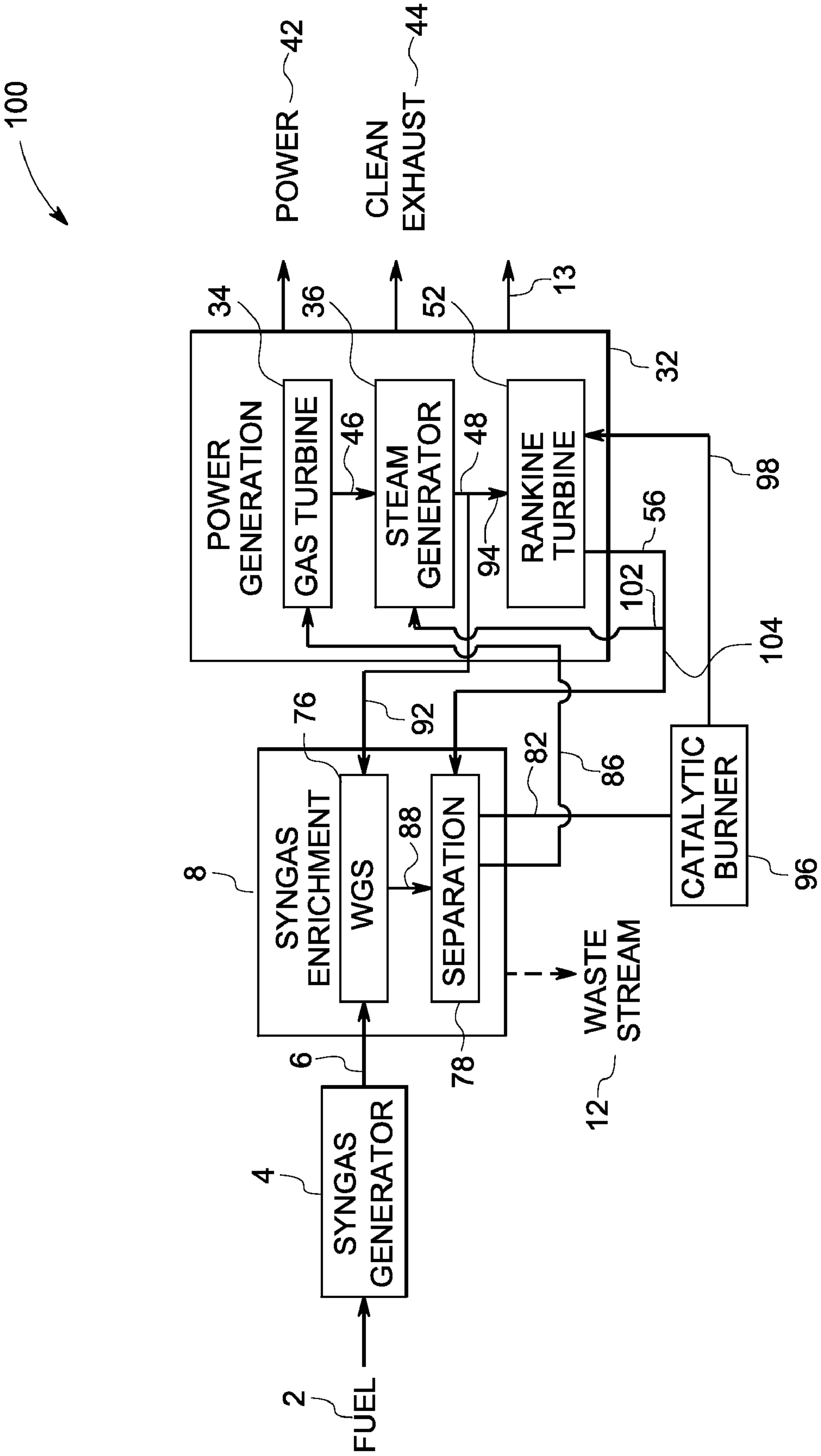


FIG. 10

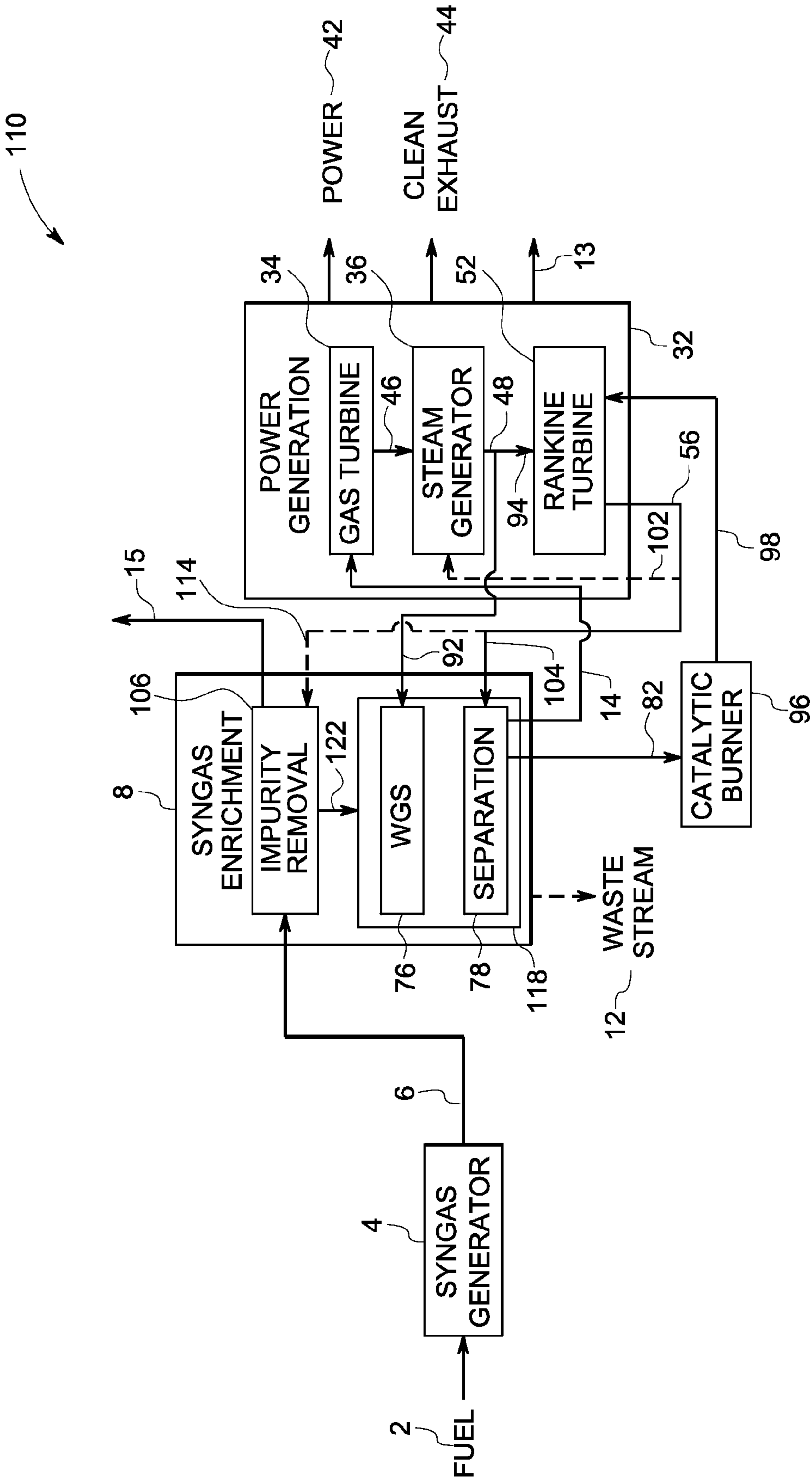


FIG. 11

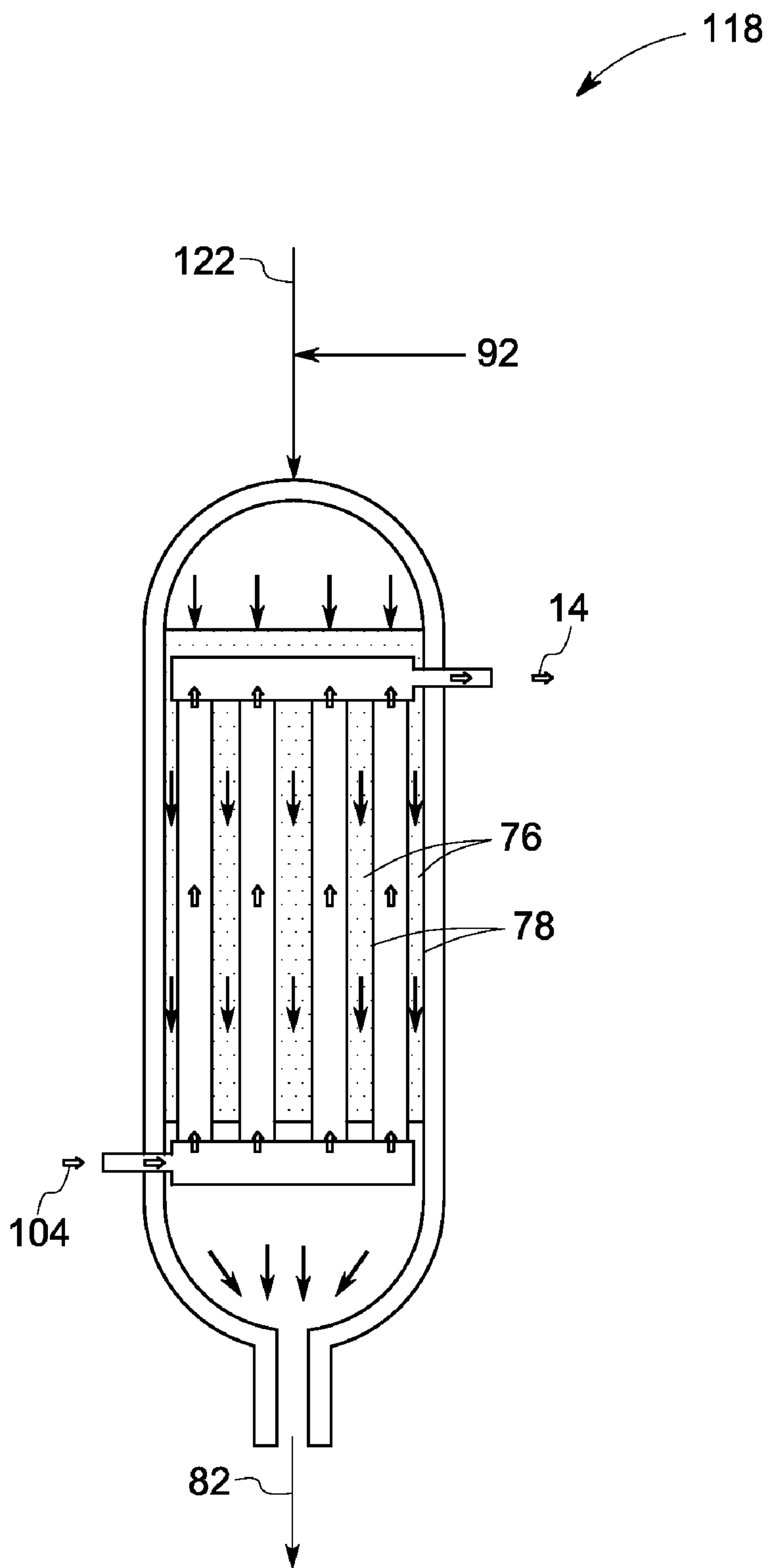


FIG. 12

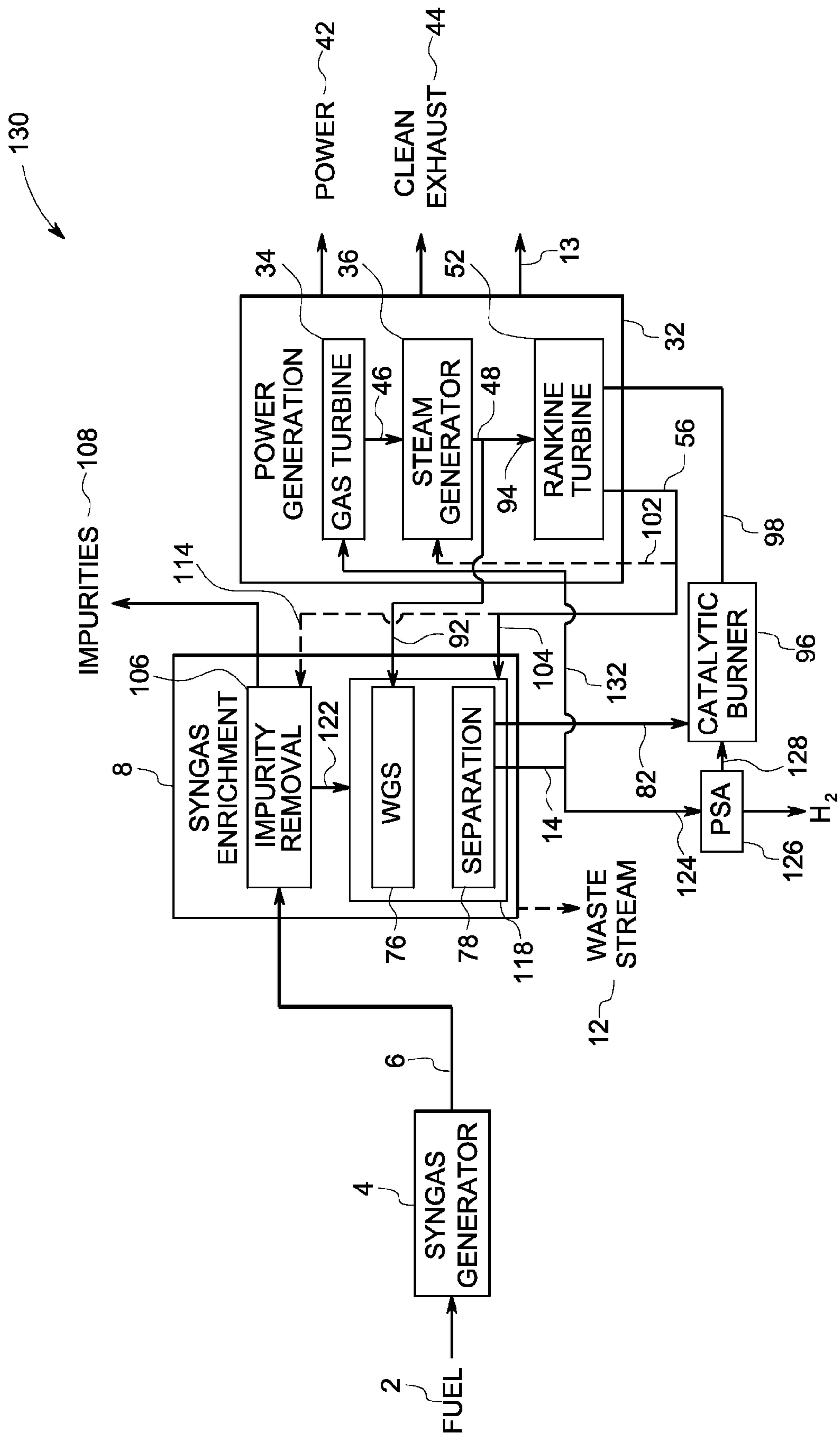


FIG. 13

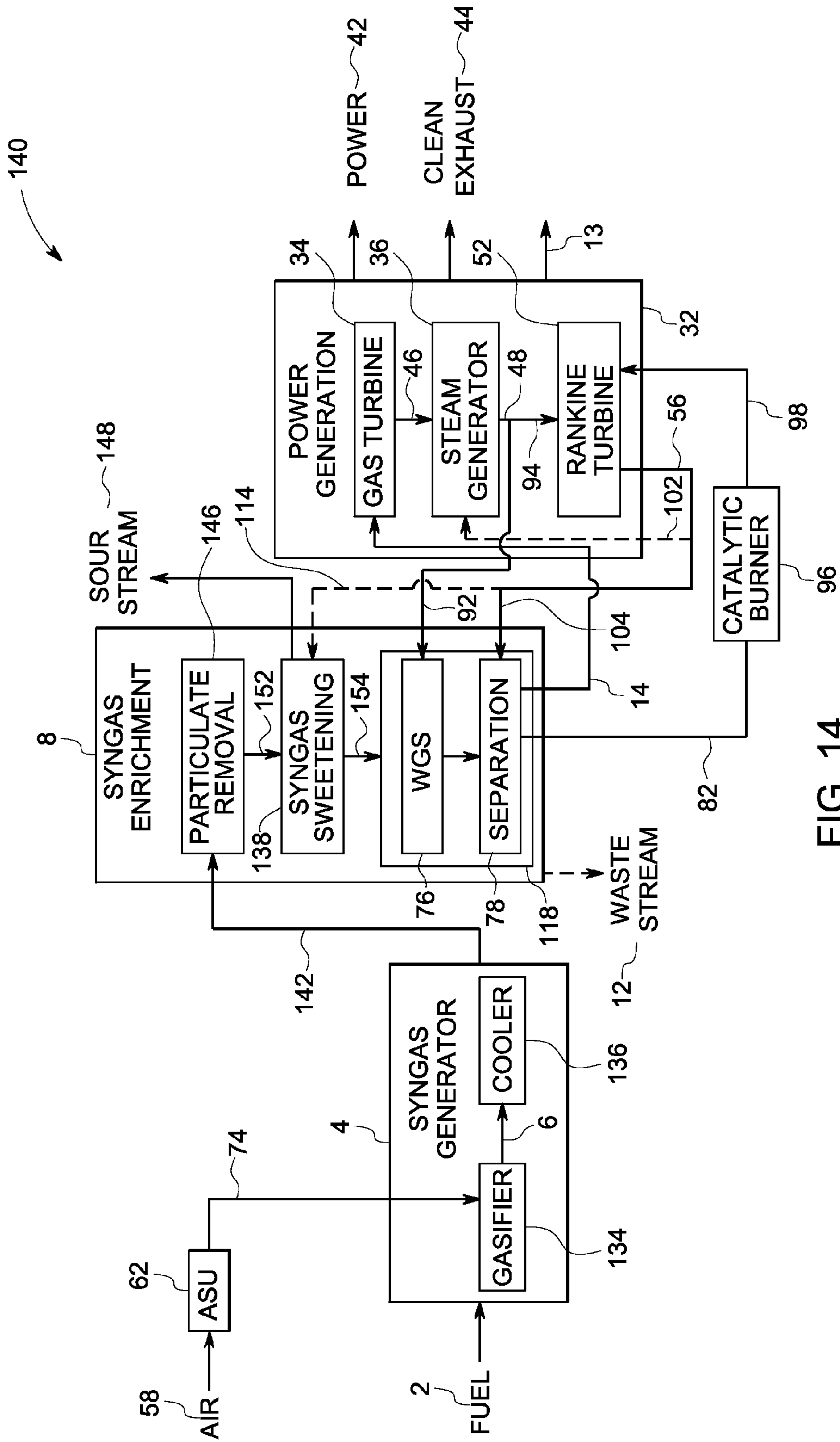


FIG. 14

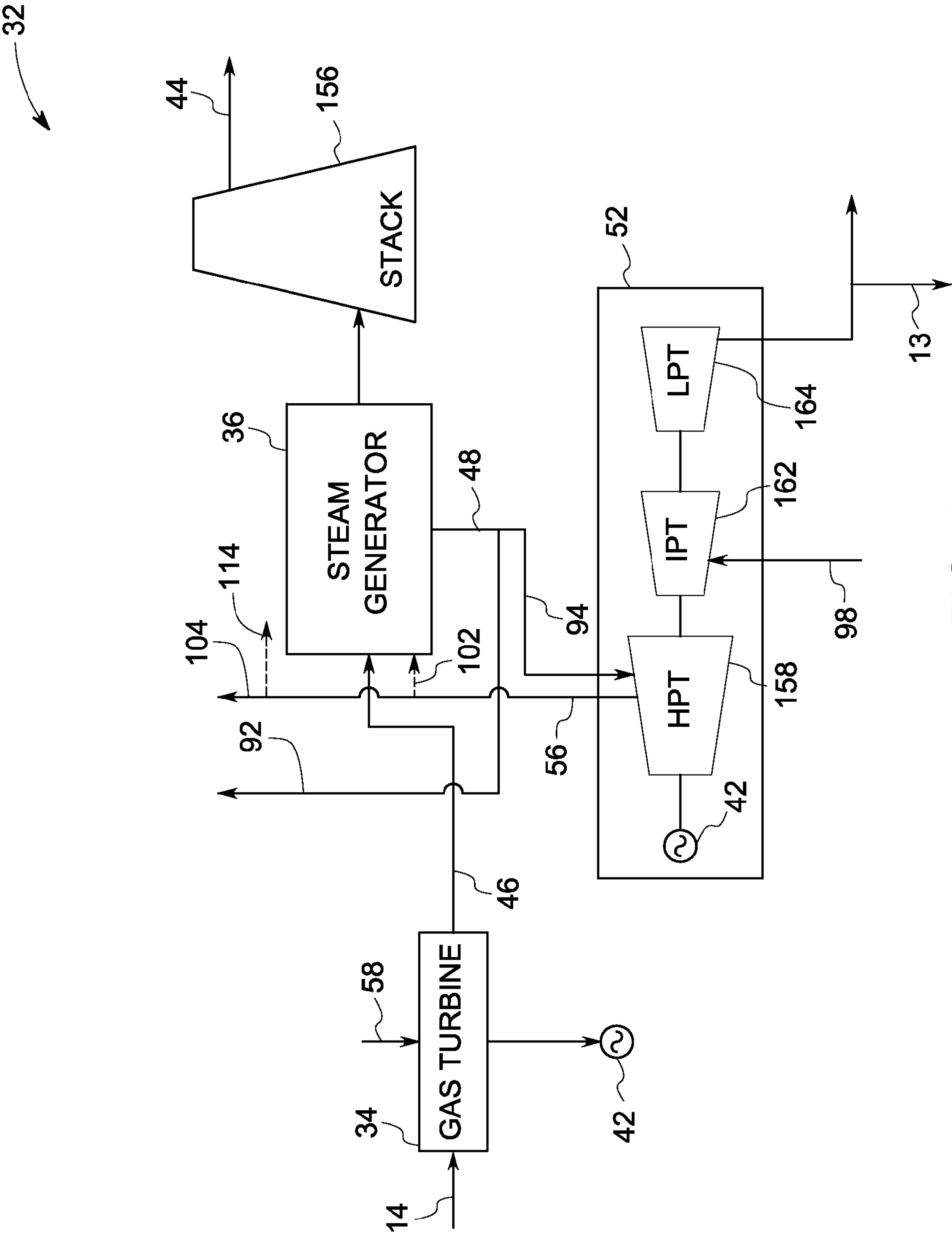


FIG. 15

POLYGENERATION SYSTEMS

[0001] This invention was made with Government support under contract number DE-FC26-05NT42451 awarded by Department of Energy. The Government has certain rights in the invention.

BACKGROUND

[0002] The invention relates generally to a polygeneration system and more specifically to integrating the various units of a polygeneration system to effectively separate the undesired species.

[0003] The effect of industrialization on the environment has been a subject of many scientific debates and recent discussions are focused on the effect of greenhouse gases on global warming. Power generation and large chemical industries are among the contributors to the total greenhouse gas emissions. These are single point sources of emissions compared to the distributed nature of emissions from other sources such as the automobile. Containing the greenhouse gas emissions from single point sources such as power generation is desirable in reducing the total greenhouse gas emissions.

[0004] There are various technologies being developed for reducing the greenhouse gas emissions, especially carbon dioxide from power plants as well as chemical industries. Both pre-combustion and post-combustion capture of carbon dioxide are the focus of intense studies in the recent times. In order to make power generation or chemical production an environmentally friendly process, it is important to separate all the undesired species, including carbon dioxide that would have otherwise been emitted to the environment. Separation of undesired species adds to the total cost of producing power or chemicals, hence technologies that enable capture of these undesired species efficiently are desired.

BRIEF DESCRIPTION

[0005] According to one aspect, a polygeneration system is provided that includes a syngas generator for producing a syngas, a syngas enrichment unit for separating undesired species from the syngas to produce an enriched syngas and a syngas utilization system that utilizes the enriched syngas to produce useful products and a stream to facilitate the separation of undesired species in the syngas enrichment unit. In some embodiments, the polygeneration system includes a gasifier, a particulate removal unit, a water gas shift unit and a power generation unit.

[0006] In another aspect, a polygeneration system includes a syngas generator for producing syngas, a syngas enrichment unit for separating undesired species from the syngas to produce an enriched syngas and a power generation unit that includes a gas turbine system for combusting the enriched syngas and to produce a hot expanded gas. The hot expanded gas is used to produce a first portion of steam in the steam generation system. The power generation system includes a steam turbine system that uses the first portion of steam from the steam generation system to produce power and a second portion of steam. The second portion of steam is used to facilitate separation of the undesired species in the syngas enrichment unit.

[0007] In yet another aspect, a polygeneration system includes a syngas generator for producing syngas, a syngas

enrichment unit for separating undesired species from the syngas to produce an enriched syngas and a fluid stream comprising said undesired species. The polygeneration system includes a power generation unit that includes a gas turbine system for combusting the enriched syngas and a hot expanded gas. The hot expanded gas is used to produce a first portion of steam in the steam generation system. The power generation system includes a rankine turbine that uses said first portion of steam and the fluid stream comprising said undesired species from the syngas enrichment unit to produce power and a second portion of steam. The second portion of steam is used to facilitate the separation of said undesired species in the syngas enrichment unit.

[0008] In yet another aspect, a polygeneration system includes a syngas generator for producing a syngas, a syngas enrichment unit that includes a water gas shift unit and a separation unit. The water gas shift unit receives said syngas and produces a hydrogen enriched syngas. The undesired species are separated from the hydrogen enriched syngas to produce an enriched syngas and a fluid stream comprising said undesired species. The polygeneration system includes a power generation unit comprising a gas turbine system, a steam generation system and a rankine turbine system. The enriched syngas is combusted in the gas turbine system to produce power and a hot expanded gas. The hot expanded gas is received by the steam generation system to produce a first portion and a second portion of steam. The first portion of steam and the fluid stream comprising said undesired species are received by the rankine turbine system to produce power and a third portion of steam. The third portion of steam is provided to the separation unit to facilitate the separation of said undesired species.

[0009] In yet another aspect, a polygeneration system comprises an air separation unit, a syngas generator, a syngas enrichment unit, a catalytic burner and a power generation unit. An oxygen rich stream is produced in the air separation unit, which is sent to the syngas generator. The syngas generator includes a gasifier that is configured to receive a carbonaceous fuel and said oxygen rich stream to produce syngas. The syngas generator further includes a cooling unit to receive said syngas and to produce a cooled syngas. The syngas enrichment unit comprises a particulate removal unit, a syngas sweetening unit, a water gas shift reactor and a separation unit. The cooled syngas is received by the particulate removal unit to produce a particulate free syngas, which is received by the syngas sweetening unit to produce a sweet syngas. The water gas shift unit is configured to receive said sweet syngas and a first portion of steam to produce an hydrogen enriched syngas and a first portion of steam. The separation unit is configured to receive said hydrogen enriched syngas to produce an enriched syngas and a fluid stream comprising said undesired species. The fluid stream comprising said undesired species is sent to the catalytic burner to produce a non-flammable stream. The power generation unit comprises a gas turbine system, a steam generation system and a rankine turbine system. The gas turbine is configured to receive said enriched syngas to produce power and a hot expanded gas, which is received by the steam generation system to produce said first portion of steam and a second portion of steam. The rankine turbine system receives said second portion of steam and said non-flammable fluid stream to produce power and a third portion of steam, which is sent to said separation unit to facilitate separation of said undesired species.

DRAWINGS

[0010] These and other features, aspects, and advantages of the present invention will become better understood when the

following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

[0011] FIG. 1 depicts a first embodiment of the instant invention;

[0012] FIG. 2 depicts a second embodiment of the instant invention;

[0013] FIG. 3 depicts a third embodiment of the instant invention;

[0014] FIG. 4 depicts a fourth embodiment of the instant invention;

[0015] FIG. 5 depicts a fifth embodiment of the instant invention;

[0016] FIG. 6 depicts a sixth embodiment of the instant invention;

[0017] FIG. 7 depicts a seventh embodiment of the instant invention;

[0018] FIG. 8 depicts a eighth embodiment of the instant invention;

[0019] FIG. 9 depicts a ninth embodiment of the instant invention;

[0020] FIG. 10 depicts a tenth embodiment of the instant invention;

[0021] FIG. 11 depicts a eleventh embodiment of the instant invention;

[0022] FIG. 12 depicts an exemplary membrane reactor;

[0023] FIG. 13 depicts a twelfth embodiment of the instant invention;

[0024] FIG. 14 depicts a thirteenth embodiment of the instant invention; and

[0025] FIG. 15 depicts an exemplary power generation unit.

DETAILED DESCRIPTION

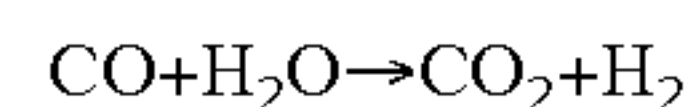
[0026] A polygeneration system 10 includes a syngas generator 4, a syngas enrichment unit 8 and a syngas utilization system 18, as shown in FIG. 1. A carbonaceous fuel 2 is converted to a syngas 6 in the syngas generator 4, which syngas 6 typically includes hydrogen and carbon monoxide. The syngas 6 is enriched in the syngas enrichment unit 8 to produce an enriched syngas 14. The enriched syngas 14 is used in the syngas utilization system 18 to produce useful products 22. A fluid stream 16 from the syngas utilization system 18 is used to facilitate the syngas enrichment in the syngas enrichment unit 8 to produce the enriched syngas 14 from the syngas 6.

[0027] Carbonaceous fuel 2 comprises, for example, coal, oil, natural gas, biomass, waste, or any other carbonaceous material. The carbonaceous fuel 2 is converted to the syngas 6 in the syngas generator 4 by a conventional process, including, but not limiting to gasification, partial oxidation, reforming and auto-thermal reforming. In one embodiment, the syngas generator 4 comprises a reactor unit and includes for example, a reformer; a partial oxidation (POX) reactor; an autothermal reactor and a gasifier. In one embodiment, the syngas generator 4 may further comprise a provision for cooling the syngas 6. In another embodiment, unconverted carbonaceous fuel in the syngas generator 4 is recycled back (not shown in FIG. 1) to be mixed with the carbonaceous fuel 2.

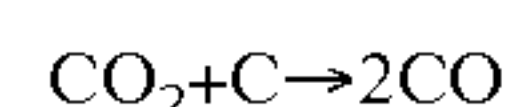
[0028] In the syngas enrichment unit 8, the syngas 6 is enriched to produce the enriched syngas 14. Enrichment of syngas 6 is typically achieved by increasing the hydrogen and/or carbon monoxide concentration in the syngas 6. The

syngas 6 may include some undesired species that can be separated from the syngas 6 in the syngas enrichment unit 8. In one embodiment, enrichment of the syngas 6 is achieved by separating the undesired species. The undesired species includes, but is not limited to particulates, sulfur compounds, carbon compounds, chlorine compounds, nitrogen compounds, water, mercury and ammonia. Some of the undesired species originate from the carbonaceous fuel 2, while the others get generated in the syngas generator 4. In one embodiment, the syngas enrichment unit 8 is configured to produce a waste stream 12 containing the undesired species. In one embodiment, separating at least a portion of the undesired species in the syngas enrichment unit 8 increases the hydrogen and/or carbon dioxide concentration in the syngas 6.

[0029] In one embodiment, the hydrogen concentration in the syngas 6 is increased by a reaction of syngas 6 with water or steam, generally known as a water gas shift reaction. The water gas shift reaction is an inorganic chemical reaction in which water and carbon monoxide react to form carbon dioxide and hydrogen and is represented as



[0030] In one embodiment, removing at least a portion of the hydrogen from the syngas 6 increases the carbon monoxide concentration. In another embodiment, the carbon monoxide concentration in the syngas 6 is increased by the reaction of carbon dioxide and carbon to form carbon monoxide, generally known as reverse boudouard reaction, which is represented by



[0031] The syngas utilization system 18 is a unit that produces the useful products 22, including for example, power and chemicals. The syngas utilization system 18 is configured to receive the enriched syngas 14 and to produce the fluid stream 16. In one embodiment, the fluid stream 16 facilitates syngas enrichment by providing the heat required for the syngas enrichment. In another embodiment, the fluid stream 16 provides the pressure required for the syngas enrichment. In yet another embodiment, the fluid stream 16 provides the steam requirements of the syngas enrichment.

[0032] A polygeneration system 20 of the instant invention is shown in FIG. 2. The exemplary polygeneration system 20 includes the syngas generator 4, the syngas enrichment unit 8 and the syngas utilization system 18. In one embodiment, the syngas utilization system 18 includes a chemical synthesis unit 24 producing the chemicals or a power generation unit 32 producing the power or both. In one embodiment, as shown in FIG. 2, the syngas utilization system 18 includes both the chemical synthesis unit 24 and the power generation unit 32.

[0033] The chemical synthesis unit 24 is configured to receive a portion of the enriched syngas 14 from the syngas enrichment unit 8 to produce the chemicals including hydrogen, ammonia, dimethyl ether, methanol or liquid hydrocarbons. In one embodiment, the chemical synthesis unit 24 employs Fischer-Tropsch process to produce hydrocarbons such as but not limited to gasoline and diesel. The power generation unit 32 is configured to receive a portion of the enriched syngas 14 as a fuel source to produce the power.

[0034] In one embodiment, the power generation unit 32 is a combined cycle power plant. A typical combined cycle power plant includes a gas turbine plant, a heat recovery steam generator (HRSG) and a steam turbine plant. In the gas turbine plant, a fuel is combusted to produce a pressurized combusted gas that is expanded to produce the power and the

hot expanded gas from the gas turbine is sent to the HRSG, which produces high-pressure steam that is expanded in a steam turbine plant to generate additional power. Using the enriched syngas **14** as the fuel source in the combined cycle power plant has many advantages including clean and efficient burning of the fuel, clean exhaust to the atmosphere, and efficient capture of greenhouse gases including carbon dioxide. In one embodiment, the power generation unit **32** is a simple cycle gas turbine plant using the enriched syngas **14** as a fuel source. In another embodiment, the power generation unit **32** is a steam turbine plant that uses the enriched syngas **14** in boilers either as a single source of fuel or combined with other fuels to produce high-pressure steam that runs the steam turbine. Other fuels that can be used along with the enriched syngas **14** include but are not limited to coal, biomass, oil and natural gas.

[0035] As described in the previous embodiment, the fluid stream **16** from the syngas utilization system **18** facilitates the enrichment of the syngas **6** in the syngas enrichment unit **8**. In one embodiment, the fluid stream **16** is an inert gas stream from the chemical synthesis unit **24**. In another embodiment, the fluid stream **16** is steam generated in the HRSG. In yet another embodiment, the fluid stream **16** is the steam partially expanded in the steam turbine.

[0036] A polygeneration system **30** of the instant invention is shown in FIG. **3**. In the exemplary polygeneration system **30**, the power generation unit **32** includes a gas turbine **34**, a steam generator **36** and a steam turbine **38**. The power generation unit **32** produces power **42** and a clean exhaust **44**. The clean exhaust **44** has lower concentration of emissions as compared to that from a conventional pulverized coal power plant. The emissions include but are not limited to nitrogen compounds, sulfur compounds, chlorine compounds, mercury, ammonia and carbon dioxide. The gas turbine **34** includes a compressor to compress an oxygen containing stream (oxidant) such as air, a combustor for combusting the fuel with the compressed oxidant to generate the pressurized combusted gas (not shown in FIG. **3**). In one embodiment, the enriched syngas **14** is used as the fuel in the combustor of the gas turbine **34**. The gas turbine **34** includes an expander to expand the pressurized combusted gas, which expander is coupled to a generator (not shown in figure) to produce the power **42** and a hot expanded gas **46**. The hot expanded gas **46** from the gas turbine **34** is sent to the steam generator **36** that produces a high-pressure steam **48** using the heat content of the expanded gas **46**. The high-pressure steam **48** generated in the steam generator **36** is expanded in the steam turbine **38** to produce the power **42**.

[0037] In one embodiment, the gas turbine **34** and the steam turbine **38** are coupled to the same generator. In one embodiment, the steam turbine **38** is a reheat turbine wherein the steam flow is taken out from a high-pressure section and returned to an intermediate pressure section after adding additional heat in the steam generator **36**, thereby increasing the net power output. In one embodiment, a partially expanded fluid stream **28** is taken from the steam turbine **38** to be used in the syngas enrichment unit **8** to facilitate the separation of the undesired species from the syngas **6** to produce the enriched syngas **14**.

[0038] Separation of the undesired species from the syngas **6** is achieved by a suitable technique, including physical and chemical separation techniques. In one embodiment, the particulates in the syngas **6** are separated by washing the syngas **6** with water. In another embodiment, some of the undesired

species including the sulfur compounds are separated from the syngas **6** by scrubbing the syngas **6** with an amine solution. In yet another embodiment, some of the undesired species including sulfur compounds and carbon compounds are separated by using an absorption technique employing a solvent.

[0039] In one embodiment, a membrane separation technique is used to separate the undesired species from the syngas **6**. Driving forces in a membrane separation technique include pressure, and/or concentration difference across the membrane. In a simple membrane separation process, feed stream is fed on one side of the membrane, wherein the membrane has different permeabilities for different species, thus effecting separation of the species. Permeability is defined as the molar flow of a species across the membrane per unit area of the membrane in unit time. A carrier stream is usually employed to carry the species that permeated through the membrane, thereby increasing the efficiency of separation. The characteristics of the carrier stream are such that the separation of the permeated species from this carrier stream can be done by a simple process. In one embodiment, the fluid stream **28** is used as carrier to separate the undesired species from the syngas **6**.

[0040] In one embodiment, the undesired species to be separated in the syngas enrichment unit **8** is carbon dioxide and to achieve this separation a membrane that has high permeability to carbon dioxide is used. Steam is a preferred carrier for carbon dioxide as separating the carbon dioxide from the steam can easily be carried out by a simple process of condensation. In one embodiment, the fluid stream **28** is used as a carrier to efficiently carry the carbon dioxide that is permeated to the other side of the membrane.

[0041] A polygeneration system **40** of the instant invention is shown in FIG. **4**. In the exemplary polygeneration system **40**, the power generation unit **32** includes a rankine turbine **52**. In one embodiment, the syngas enrichment unit **8** is configured to produce the waste stream **12** containing a first portion of the undesired species and a fluid stream **54** containing a second portion of the undesired species. In one embodiment, the fluid stream **54** along with the high-pressure steam **48** is used as the working fluid in the rankine turbine **52**. Using the fluid stream **54** as the working fluid in the rankine turbine **52** in addition to the high-pressure steam **48** increases the power output from the rankine turbine **52**. The working fluid of the rankine turbine **52** may include either steam, or carbon dioxide or nitrogen or a combination thereof. In one embodiment, the rankine turbine **52** is configured to produce a fluid stream **56**, which is sent to the syngas enrichment unit **8** to facilitate the syngas enrichment.

[0042] In one embodiment, a water gas shift reaction is used for syngas enrichment in the syngas enrichment unit **8**, and the fluid stream **56** is used to provide the steam required for the water gas shift reaction. In one embodiment, a solvent is employed to separate the undesired species in the syngas enrichment unit **8**, and the fluid stream **56** is used to provide the heat required for solvent regeneration. In another embodiment, a membrane separation technique is employed in separating the undesired species in the syngas enrichment unit **8**, and the fluid stream **56** is used as a carrier for the undesired species that are permeated across the membrane. In one embodiment, a first portion of the undesired species is separated as the waste stream **12** in the syngas enrichment unit **8** shown by a dotted line in FIG. **4**. The fluid stream **54** carrying the second portion of the undesired species is expanded in the

rankine turbine **52** and the second portion of the undesired species is separated as a fluid stream **13** from the power generation unit **32**. In one embodiment, the undesired species are separated from the syngas enrichment unit **8** as the waste stream **12** or from the power generation unit **32** as the fluid stream **13** or both.

[0043] A polygeneration system **50** of the instant invention is shown in FIG. **5**. The exemplary polygeneration system **50** includes the chemical synthesis unit **24**. In one embodiment, a first portion **53** of the enriched syngas **14** is sent to the chemical synthesis unit **24**. In another embodiment, a second portion **55** of the enriched syngas **14** is sent to the gas turbine **34** of the power generation unit **32**. The combined production of chemicals and power provides an opportunity to integrate these two processes to efficiently and economically produce both the power and the chemicals.

[0044] A polygeneration system **60** of the instant invention is shown in FIG. **6**. The exemplary polygeneration system **60** includes an air separation unit (ASU) **62**. In one embodiment, air **58** is separated in the air separation unit **62** into an oxygen rich stream **74** and an oxygen lean stream **68**. Throughout this document, a fluid stream is said to be rich in a species if its concentration is greater than that in the stream from which it is generated. On the other hand, a fluid stream is said to be lean in a species if its concentration is less than that in the stream from which it is generated.

[0045] In one embodiment, the oxygen rich stream **74** is sent to the syngas generator **4**. Using the oxygen rich stream **74** instead of the air **58** to generate the syngas **6** has the advantage of smaller volume of the syngas generator **4**. Another advantage of using oxygen rich stream is the increase in the calorific value of the syngas generated. In another embodiment, a first portion **66** of the fluid stream **56** is used to facilitate air separation in the air separation unit **62** and a second portion **64** of the fluid stream **56** is sent to the syngas enrichment unit **8** to facilitate the syngas enrichment. In one embodiment, a membrane separation technique is employed in the air separation unit **62** and the fluid stream **66** is used as a carrier for the species that is permeated across the membrane. In one embodiment, the membrane is permeable to oxygen. The oxygen lean stream **68** from the ASU **62** is mixed with the fluid stream **54** coming from the syngas enrichment unit **8** to form a mixed stream **72**, which mixed stream **72** is sent to the rankine turbine **52**. Addition of the oxygen lean stream **68** to the fluid stream **54** to form mixed stream **72** increases the mass flow to the rankine turbine **52**, thereby increasing the net power output. The mixed stream **72** and the high-pressure steam **48** from the steam generator **36** are used as working fluid in the rankine turbine **52**. In one embodiment, a portion of the oxygen lean stream **68** is sent to the gas turbine **34** as a cooling agent shown by a dotted line in FIG. **6** to increase the efficiency of the power generation. Throughout this document a dotted line indicates an optional embodiment. In another embodiment, the compressor of the gas turbine unit **34** is used to compress the air **58** of the air separation unit **62** (not shown in FIG. **6**).

[0046] A polygeneration system **70** of the instant invention is shown in FIG. **7**. The exemplary polygeneration system **70** includes a water gas shift (WGS) unit **76** and a separation unit **78**. In one embodiment, the syngas **6** from the syngas generator **4** is sent to the water gas shift unit **76**, wherein the water gas shift reaction takes place to produce a hydrogen enriched syngas **88**, rich in hydrogen. In one embodiment, the hydrogen enriched syngas **88** is sent to the separation unit **78**, to

produce a fluid stream **82** carrying a portion of the undesired species. In one embodiment, pluralities of separation unit **78** are employed to separate the undesired species. In one embodiment, the separation unit **78** is a membrane separator. In one embodiment, the fluid stream **82** comprising a portion of the undesired species from the separation unit **78** is sent to the rankine turbine **52** as a working fluid. The fluid stream **56** is drawn from the rankine turbine at appropriate pressure and temperature conditions to maximize the overall efficiency of the polygeneration system. In one embodiment, the fluid stream **56** is drawn at the operating pressure and temperature of the water gas shift unit **76**. In another embodiment, the fluid stream **56** is drawn from the rankine turbine **52** at the operating conditions of the separation unit **78**. In yet another embodiment, the fluid stream **82** is lean in hydrogen and contains a portion of the fluid stream **56**.

[0047] The WGS unit **76** can be a catalytic or non-catalytic reactor unit. Some catalysts used in the WGS unit **76** include but not limited to the oxides of iron, chromium, copper, zinc, cobalt, and molybdenum. The WGS unit **76** can use either a sour syngas comprising sulfur compounds or a sweet syngas devoid of sulfur compounds. Devoid is to be understood as low concentration of a species rather than the absence of that species. The water gas shift reaction is an exothermic reaction and hence generates heat. In one embodiment, the heat generated in the water gas shift reaction is removed from the WGS unit **76**.

[0048] A polygeneration system **80** of the instant invention is shown in FIG. **8**. The high-pressure steam **48** is split into two streams, a first portion **92** and a second portion **94**. In one embodiment, the high-pressure fluid stream **92** provides the steam required for the water gas shift reaction in the WGS unit **76**, thereby enabling the operation of the WGS unit **76** at high pressure. Operating the WGS unit **76** at high pressure is advantageous, as it requires smaller volume of the water gas shift unit **76**. In one embodiment when the syngas generator **4** is operated at high pressure, operating the WGS unit **76** at high pressure improves the overall system efficiency. In another embodiment, the rankine turbine **52** is configured to receive the fluid stream **94** at high pressure, which fluid stream **94** is partially expanded to produce the fluid stream **56** at a lower pressure than the fluid stream **94**. In one embodiment, the fluid stream **56** drawn from the rankine turbine **52** is sent to the separation unit **78** to facilitate the production of the enriched syngas **14** from the hydrogen enriched syngas **88**. Using the high-pressure stream **94** for the water gas shift reaction in WGS unit **76** and the low-pressure stream **56** for the separation unit is especially advantageous when a pressure driven membrane separation process is employed.

[0049] A polygeneration system **90** of the instant invention is shown in FIG. **9**. The exemplary polygeneration system **90** includes a catalytic burner **96** that is configured to receive the fluid stream **82** from the separation unit **78**. In one embodiment, the fluid stream **82** from the separation unit **78** comprises hydrogen or carbon monoxide that is burned in the catalytic burner **96**. When a membrane separation technique is used in the separation unit **78**, some amount of hydrogen and carbon monoxide permeate across the membrane along with the undesired species that are separated in the separation unit **78** and thus become part of the fluid stream **82**, which is sent to the rankine turbine **52** as a working fluid. It is desirable to limit the concentration of hydrogen and/or carbon monoxide in the fluid stream that is used as a working fluid in the rankine turbine **52** for at least two reasons. One is the loss of

the calorific value of these species when they are separated from the power generation unit 32 and another is the safety hazard that hydrogen and carbon monoxide could pose owing to their flammable nature if let into the atmosphere in the power generation unit 32. Thus, using the catalytic burner 96 that is capable of operating at very low concentration of hydrogen and/or carbon dioxide is advantageous. In one embodiment, the catalytic burner 96 is configured to receive the fluid stream 82 carrying a portion of the undesired species and to produce heat and a non-flammable fluid stream 98.

[0050] A polygeneration system 100 of the instant invention is shown in FIG. 10. In one embodiment of the exemplary polygeneration system 100, the fluid stream 56 from the rankine turbine 52 is split into two streams, a first portion 102 and a second portion 104. In one embodiment, the fluid stream 102 is sent to the steam generator 36 and the fluid stream 104 is sent to the separation unit 78 of the syngas enrichment unit 8. One advantage of sending the fluid stream 102 to steam generator 36 is to increase the heat content, which in turn increases the overall efficiency of the polygeneration system 100.

[0051] A polygeneration system 110 of the instant invention is shown in FIG. 11. The exemplary polygeneration system 110 includes the syngas enrichment unit 8 comprising an impurity removal unit 106 and a membrane reactor 118. The impurity removal unit 106 separates a portion of the undesired species from the syngas 6 and produces a purified syngas 122. In one embodiment, the water gas shift unit 76 and the separation unit 78 are combined into the membrane reactor 118. The membrane reactor 118 is configured to receive the purified syngas 122 and to produce the enriched syngas 14 and the fluid stream 82 carrying a portion of the undesired species. In one embodiment, the fluid stream 56 drawn from the rankine turbine 52 is split into three streams, the first fluid stream 102 that is sent to the steam generator 36, the second fluid stream 104 that is sent to the separation unit 78 of the membrane reactor 118 and a third fluid stream 114 that is sent to the impurity removal unit 106.

[0052] In one embodiment, the impurity removal unit 106 substantially removes some of the undesired species as part of a fluid stream 15, including, but is not limited to, particulates, oxides of sulfur, chlorine compounds and ammonia. Substantial removal of the undesired species is removing about 80% to about 95% of the total impurities. Usually the membrane reactor 118 has limited capability to handle certain types of the undesired species such as particulates and hence it is necessary to remove these undesired species before the syngas 6 is sent to the membrane reactor 118.

[0053] The membrane reactor 118 has a suitable configuration including for example, hollow fiber module, spiral wound module, plate and frame type membrane modules. In one exemplary configuration shown in FIG. 12, the membrane reactor 118 is a hollow fiber membrane module. In the membrane reactor 118 the water gas shift reaction and the separation of the undesired species takes place simultaneously, thereby altering the water gas shift reaction equilibrium enhancing conversion. The enhanced conversion allows smaller reactor volumes of the water gas shift unit 76, thereby helping in improving the overall system efficiency. In one embodiment, the water gas shift catalyst is in the shell side as shown in FIG. 12. The flow of streams on either side of the membrane can be in the same direction (co-current flow) or in opposite direction (counter-current flow). In one embodiment, the flow of streams on shell and tube side of the mem-

brane reactor 118 is counter-current as shown in FIG. 12. In another embodiment, the flow is co-current (not shown in FIG. 12).

[0054] Referring to the exemplary polygeneration system 110 shown in FIG. 11 and the membrane reactor 118 shown in FIG. 12, in one embodiment the purified syngas 122 from the impurity removal unit 106 and the fluid stream 92 from the steam generator 36 are sent on the shell side of the membrane reactor 118, wherein the water gas shift reaction takes place producing carbon dioxide and hydrogen. In one embodiment, the water gas shift catalyst is placed on the shell side. In another embodiment, there is a provision to take out the heat generated by the water gas shift reaction (not shown in FIG. 9).

[0055] In one embodiment, the membrane is permeable to carbon dioxide and the fluid stream 104 is used as the carrier for the carbon dioxide that is permeated across the membrane wall of the membrane reactor 118. By using a membrane that is selectively permeable to the carbon dioxide, simultaneous separation of the carbon dioxide and increasing the conversion of the purified syngas 122 to produce hydrogen is achieved. Another advantage of employing the membrane reactor 118 is that the water gas shift reaction can be conducted at high pressure, which improves the overall system efficiency when the purified syngas 122 is available at high pressure. The driving force for separation in the membrane reactor 118 is the pressure difference across the membrane and using the high-pressure steam 92 as a reactant and the low-pressure flow stream 104 as the carrier for the carbon dioxide provides this driving force.

[0056] The fluid stream 82 carrying the components, including, but not limited to carbon dioxide, hydrogen, carbon monoxide that are permeated across the membrane is sent to the catalytic burner 96 to produce the non-flammable fluid stream 98 that is sent to the rankine turbine 52 as a working fluid along with the high pressure steam 94. The undesirable species carried by the fluid stream 98 are separated as fluid stream 13 after the fluid stream 98 is expanded in the rankine turbine 52. Thus integrating the power generation unit 32 with the syngas enrichment unit 8 improves the overall efficiency of the polygeneration system of this invention.

[0057] In another embodiment the fluid stream 114 is used to facilitate the removal of the undesired species from the impurity removal unit 106 to produce a fluid stream 15 carrying a portion of the undesirable species. As described in the previous embodiment, the undesired species is separated either in the syngas enrichment unit 8 or in the power generation unit 32 or both.

[0058] A polygeneration system 130 of the instant invention is shown in FIG. 13. The exemplary polygeneration system 130 includes a pressure swing adsorption unit (PSA) 126 to produce high purity hydrogen. The purity of hydrogen from a PSA unit 126 is above about 95%. In one embodiment, a first portion 124 of the enriched syngas 14 from the syngas enrichment unit 8 is sent to the PSA unit 126 to produce high purity hydrogen (shown as H₂ in FIG. 13) and a PSA offgas stream 128, containing some hydrogen. In one embodiment, the PSA offgas stream 128 is sent to the catalytic burner 96 to be burned along with the fluid stream 82 to generate additional heat and to produce the non-flammable fluid stream 98. A second portion 132 of the enriched syngas 14 is sent to the gas turbine unit 34 of the power generation unit 32.

[0059] A polygeneration system 140 of the instant invention is shown in FIG. 14. The exemplary polygeneration

system 140 includes the syngas generator 4 comprising a gasifier 134 and a syngas cooler 136, the syngas enrichment unit 8 comprising a particulate removal unit 146 and a syngas sweetening unit 138. In one embodiment, the oxygen rich stream 74 from the air separation unit 62 and the carbonaceous fuel 2 are fed to the gasifier 134 to produce the syngas 6, which is cooled in the syngas cooler 136 to produce a cool syngas 142. In one embodiment, the oxygen lean stream 68 from the air separation unit 62 is sent to the gas turbine 34 (not shown in FIG. 14). In one embodiment, the gasifier 134 and the syngas cooler 136 are combined into a single unit and in another embodiment they are separate units. In one embodiment, the syngas cooler 136 is a radiant syngas cooler and in another embodiment, the syngas cooler 136 is a quench unit. In one embodiment, the syngas enrichment unit 8 includes the particulate removal unit 146, the syngas sweetening unit 138 and the membrane reactor 118. In one embodiment, the cool syngas 142 is fed into the particulate removal unit 146 and a particulate free syngas 152 is produced. The particulate free syngas 152 is sent to the syngas sweetening unit 138 and a sweet syngas 154 and a sour stream 148 are produced. The sweet syngas 154 is further fed to the membrane reactor unit 118, wherein the sweet syngas 154 undergoes water gas shift reaction in the WGS unit 76 and the undesired species are separated in the separation unit 78 to produce the enriched syngas 14.

[0060] An exemplary power generation unit 32 is shown in FIG. 15. In one embodiment, the rankine turbine 52 includes a high-pressure turbine (HPT) 158, an intermediate pressure turbine (IPT) 162 and a low-pressure turbine (LPT) 164. In one exemplary embodiment, the enriched syngas 14 from the syngas enrichment unit is combusted in the gas turbine 34 to produce the power 42. The hot expanded gas 46 from the gas turbine 34 is sent to the steam generator 36 to produce the high-pressure steam 48 and the clean exhaust 44, which is let into the atmosphere from a stack 156. In one embodiment, the fluid stream 92 is sent to the membrane reactor 118 to participate in the water gas shift reaction. In one embodiment, the stream 92 and the enriched syngas 14 are at a pressure of about 4.5 M Pa (about 45 bar). The second portion 94 of the high-pressure steam 48 is expanded in the high-pressure turbine 158. The fluid stream 104 from the high-pressure turbine is used as carrier in the membrane reactor 118 to carry the undesired species. In one embodiment, the fluid stream 104 is at a pressure of about 4 M Pa (about 40 bar). The non-flammable stream 98 is expanded in the intermediate pressure turbine 162, which is connected to a low-pressure turbine 164. The fluid stream from the low-pressure turbine 164 is sent to a condenser, wherein the undesired species are separated as the fluid stream 13 and the remaining fluid is recirculated (not shown in FIG. 15).

[0061] While only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

1. A polygeneration system comprising:
 - a syngas generator for producing a syngas comprising carbon monoxide and hydrogen;
 - a syngas enrichment unit for receiving said syngas and for separating undesired species therefrom to produce an enriched syngas; and

a syngas utilization system for utilizing said enriched syngas to produce useful products and a fluid stream to be provided to said syngas enrichment unit to facilitate separation of said undesired species.

2. The polygeneration system in accordance with claim 1, wherein said syngas is produced from a carbonaceous fuel.

3. The polygeneration system in accordance with claim 2, wherein said carbonaceous fuel comprises coal.

4. The polygeneration system in accordance with claim 1, wherein said syngas generator comprises a gasifier and an air separation unit.

5. The polygeneration system in accordance with claim 1, wherein said syngas generator comprises at least one of a reformer, a partial oxidation reactor, an autothermal reactor or a combination thereof.

6. The polygeneration system in accordance with claim 1 further comprises a pressure swing adsorption unit.

7. The polygeneration system in accordance with claim 1, wherein said syngas generator further comprises a syngas cooling unit.

8. The polygeneration system in accordance with claim 1, wherein said syngas enrichment unit comprises a water gas shift unit.

9. The polygeneration system in accordance with claim 8, wherein said water gas shift unit is a membrane reactor.

10. The polygeneration system in accordance with claim 1, wherein said syngas enrichment unit further comprises a separation unit for substantially separating said undesired species.

11. The polygeneration system in accordance with claim 1, wherein said syngas enrichment unit further comprise an impurity removal unit.

12. The polygeneration system in accordance with claim 11, wherein said impurity removal unit substantially separates said undesired species comprising at least one of sulfur containing compounds, nitrogen containing compounds, chlorine containing compounds, carbon containing compounds, particulates or combinations thereof.

13. The polygeneration system in accordance with claim 1, wherein said syngas utilization system further comprises a power generation unit or a chemical synthesis unit or a combination thereof.

14. The polygeneration system in accordance with claim 13, wherein said power generation unit comprises at least one of gas turbine, rankine turbine, steam turbine, combustor, steam generator or combinations thereof.

15. The polygeneration system in accordance with claim 14, wherein said steam generator is configured to produce a first portion of steam and a steam turbine is configured to receive said first portion of steam and to produce a second portion of steam, wherein said second portion of steam is provided to said enrichment unit to facilitate separation of said undesired species.

16. The polygeneration system in accordance with claim 14, wherein said syngas enrichment unit is configured to produce a fluid stream comprising said undesired species and a rankine turbine is configured to receive a first portion of steam and said fluid stream comprising said undesired species to produce a second portion of steam, wherein said second portion of steam is provided to said enrichment unit to facilitate separation of said undesired species.

17. A polygeneration system comprising:
 - a syngas generator for producing a syngas comprising carbon monoxide and hydrogen;

- a syngas enrichment unit for receiving said syngas and for separating undesired species therefrom to produce an enriched syngas; and
- a power generation system comprising:
- a gas turbine system for combusting said enriched syngas to produce power and a hot expanded gas;
 - a steam generation system for receiving said hot expanded gas to produce a first portion of steam; and
 - a steam turbine system for receiving said first portion of steam to produce power and a second portion of steam, wherein said second portion of steam is provided to said enrichment unit to facilitate separation of said undesired species.
- 18.** A polygeneration system comprising:
- a syngas generator for producing a syngas comprising carbon monoxide and hydrogen;
 - a syngas enrichment unit for receiving said syngas and for producing an enriched syngas and a fluid stream comprising undesired species; and
 - a power generation system comprising:
 - a gas turbine system for combusting said enriched syngas to produce power and a hot expanded gas;
 - a steam generation system for receiving said hot expanded gas to produce a first portion of steam; and
 - a rankine turbine system that receives said first portion of steam and said fluid stream comprising undesired species to produce power and a second portion of steam, wherein said second portion of steam is provided to said enrichment unit to facilitate separation of said undesired species.
- 19.** The polygeneration system in accordance with claim **18** further comprises a chemical synthesis unit to receive a portion of said enriched syngas.
- 20.** The polygeneration system in accordance with claim **18** further comprises an air separation unit to receive a portion of said second portion of steam and to produce said fluid stream comprising said undesired species.
- 21.** A polygeneration system comprising:
- a syngas generator for producing a syngas comprising carbon monoxide and hydrogen;
 - a syngas enrichment unit comprising:
 - a water gas shift unit for receiving said syngas and for producing an hydrogen enriched syngas; and
 - a separation unit for receiving said hydrogen enriched syngas and for separating undesired species therefrom to produce an enriched syngas and a fluid stream comprising said undesired species;
 - a power generation system comprising:
 - a gas turbine system for combusting said enriched syngas to produce power and a hot expanded gas;
 - a steam generation system for receiving said hot expanded gas to produce a first portion of steam; and
 - a rankine turbine system that receives said first portion of steam and said fluid stream comprising said undesired species to produce power and a second portion of steam, wherein said second portion of steam is provided to said enrichment unit to facilitate separation of said undesired species.
- 22.** The polygeneration system in accordance with claim **21**, further comprises a catalytic burner that receives said fluid stream comprising said undesired species.
- 23.** The polygeneration system in accordance with claim **21** further comprises a pressure swing adsorption unit configured to receive said syngas and to produce an offgas stream to be received by said catalytic burner.
- 24.** A polygeneration system comprising:
- a syngas generator for producing a syngas comprising carbon monoxide and hydrogen;
 - a syngas enrichment unit comprising:
 - a water gas shift unit for receiving said syngas and a first portion of steam to produce an hydrogen enriched syngas; and
 - a separation unit for receiving said hydrogen enriched syngas and for separating undesired species therefrom to produce an enriched syngas and a fluid stream comprising said undesired species; and
 - a power generation system comprising:
 - a gas turbine system for combusting said enriched syngas to produce power and a hot expanded gas;
 - a steam generation system for receiving said hot expanded gas to produce said first portion of steam and a second portion of steam; and
 - a rankine turbine system that receives said second portion of steam and said fluid stream comprising said undesired species to produce power and a third portion of steam, wherein said third portion of steam is provided to said separation unit to facilitate separation of said undesired species
- 25.** A polygeneration system in accordance with claim **24** further comprises a chemical synthesis unit that receives a part of said enriched syngas.
- 26.** A polygeneration system in accordance with claim **24**, wherein said syngas enrichment unit further comprise a catalytic burner to receive said fluid stream comprising said undesired species.
- 27.** A polygeneration system comprising:
- an air separation unit for receiving air and producing an oxygen rich stream;
 - a syngas generator comprising:
 - a gasifier for receiving a carbonaceous fuel and said oxygen rich stream to produce syngas comprising carbon monoxide and hydrogen; and
 - a cooling unit for receiving said syngas and producing a cooled syngas;
 - a syngas enrichment unit comprising:
 - a particulate removal unit for receiving said cooled syngas and to produce a particulate free syngas;
 - a syngas sweetening unit for receiving said particulate free syngas and to produce a sweet syngas;
 - a water gas shift reactor for receiving said sweet syngas and a first portion of steam to produce an hydrogen enriched syngas; and
 - a separation unit for receiving said hydrogen enriched syngas and for separating said undesired species therefrom to produce an enriched syngas and a fluid stream comprising said undesired species;
 - a catalytic burner for receiving said fluid stream comprising said undesired species and to produce a non-flammable fluid stream; and
 - a power generation system comprising:
 - a gas turbine system for combusting said enriched syngas to produce power and a hot expanded gas;

a steam generation system for receiving said hot expanded gas to produce said first portion of steam and a second portion of steam; and
a rankine turbine system that receives said second portion of steam and said non-flammable fluid stream to produce power and a third portion of steam, wherein said third portion of steam is provided to said separa-

tion unit to facilitate the separation of said undesired species.

28. The polygeneration system in accordance with claim **27**, wherein said water gas shift reactor and said separation unit are combined into a membrane reactor.

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