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(54) **POLYGENERATION SYSTEMS**

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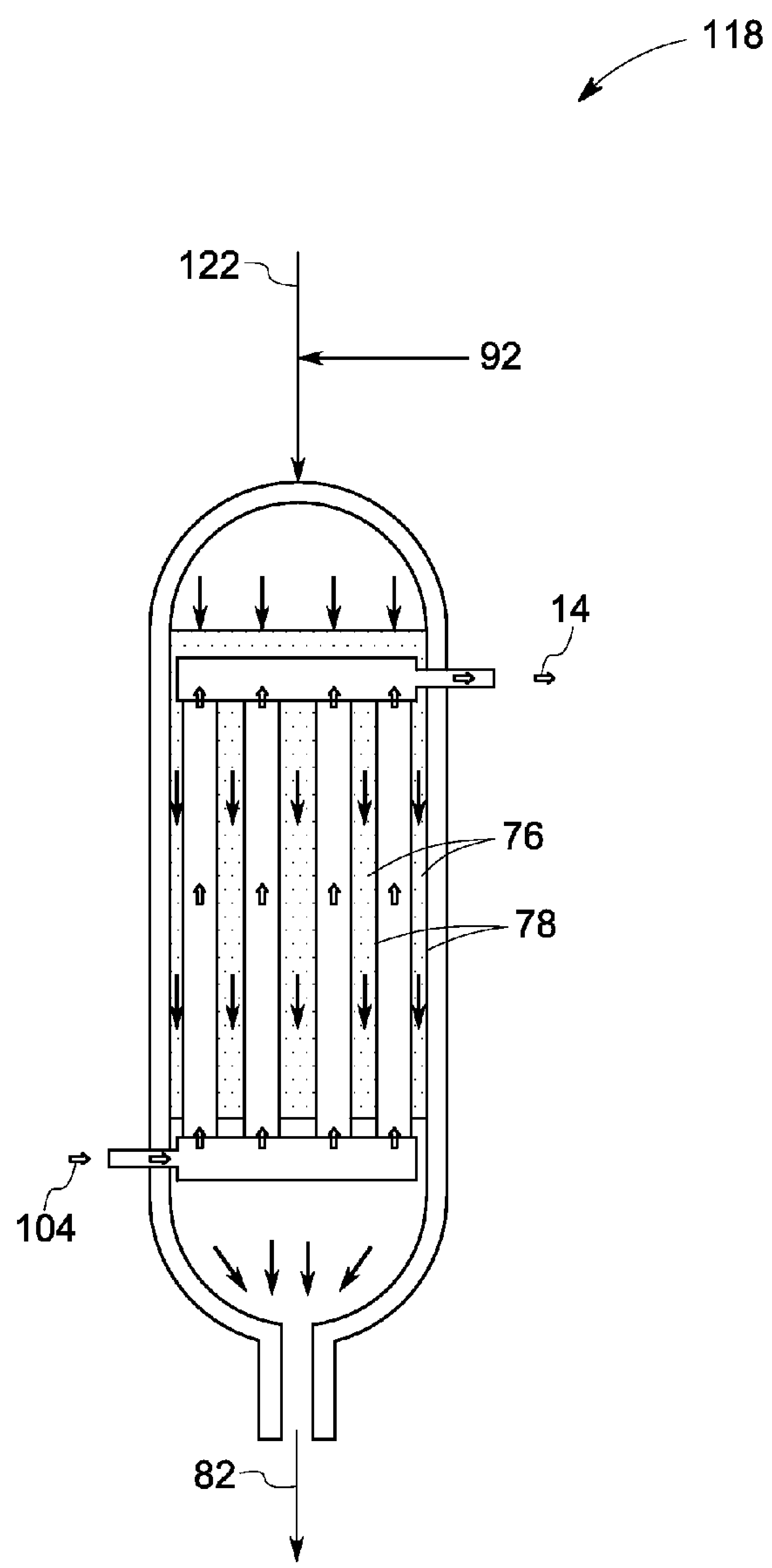
(57) **ABSTRACT**

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.



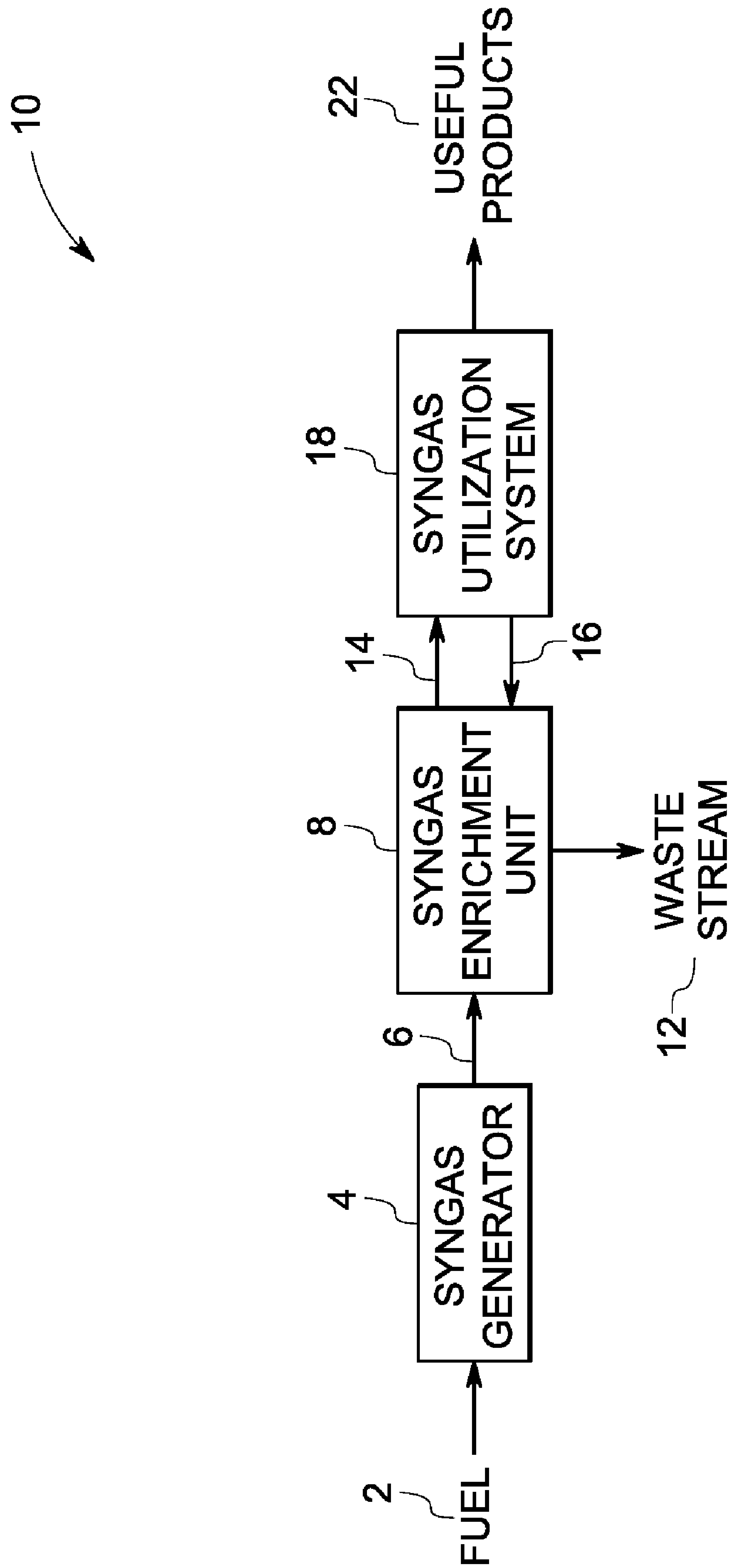
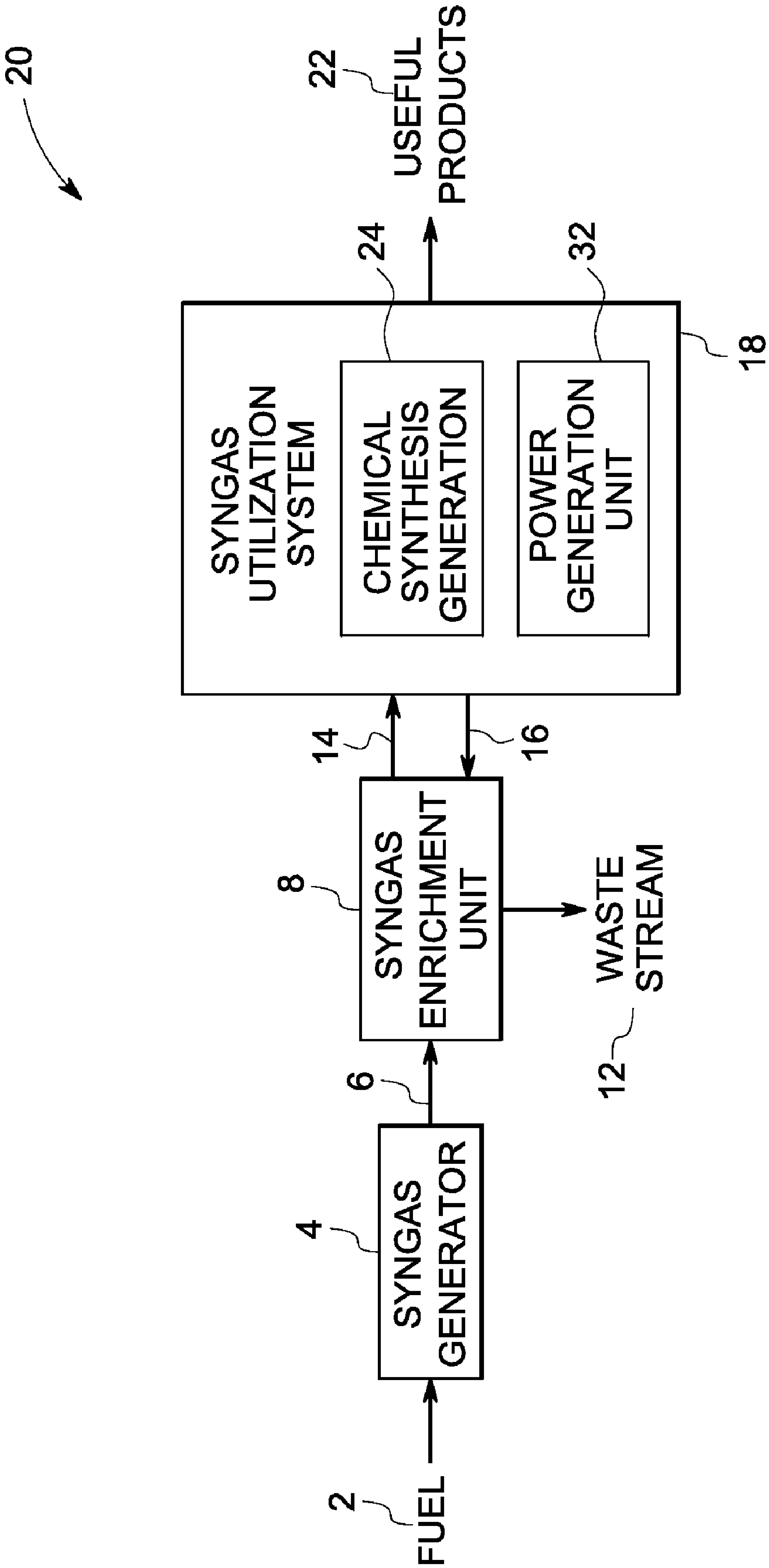

10
FUEL
2
SYNGAS GENERATOR
4
6
SYNGAS ENRICHMENT UNIT
8
WASTE STREAM
12
14
16
SYNGAS UTILIZATION SYSTEM
18
USEFUL PRODUCTS
22

FIG. 1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FUEL
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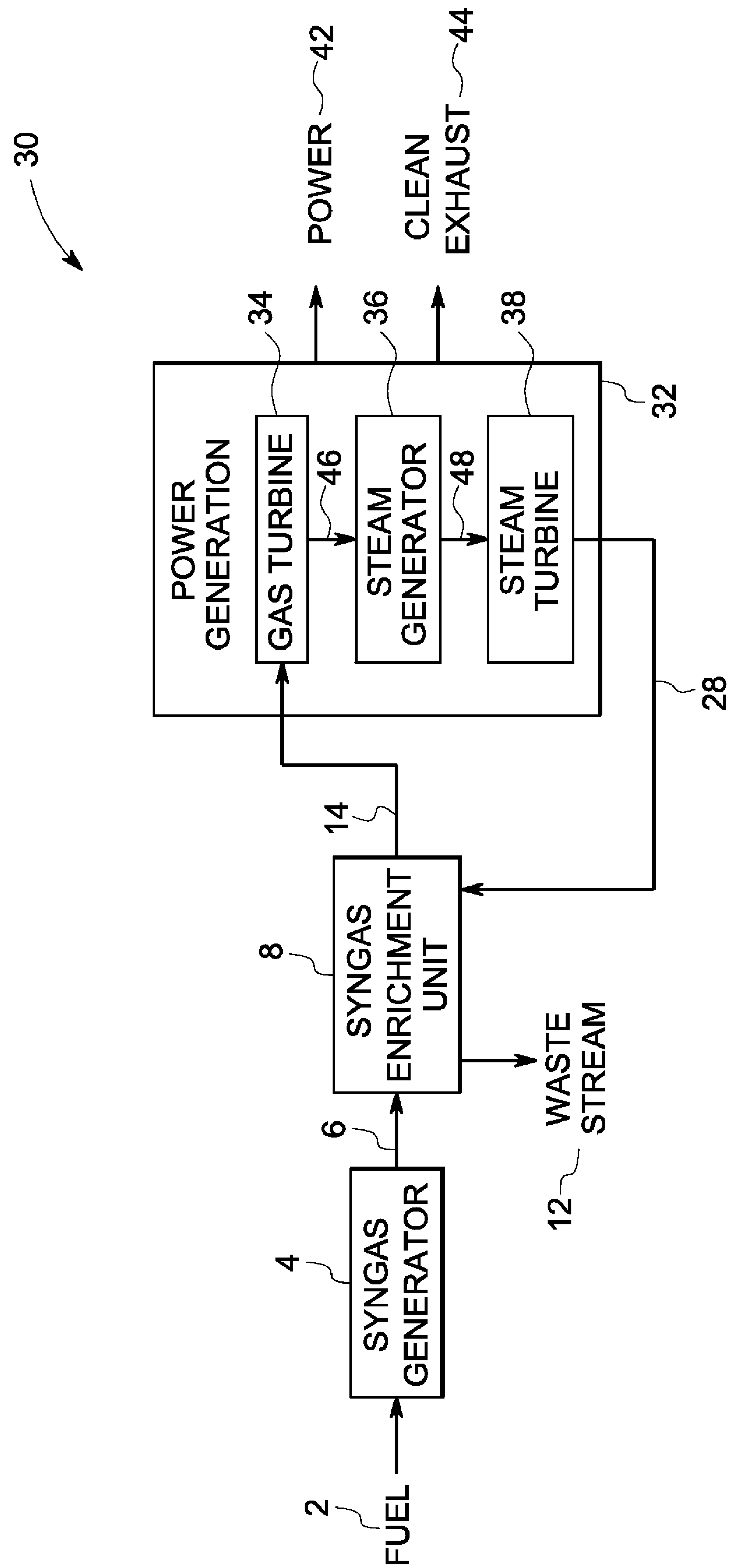
SYNGAS GENERATOR
4
6
SYNGAS ENRICHMENT UNIT
8
WASTE STREAM
12
14
16
SYNGAS UTILIZATION SYSTEM
CHEMICAL SYNTHESIS GENERATION
24
POWER GENERATION UNIT
32
18
USEFUL PRODUCTS
22

FIG. 2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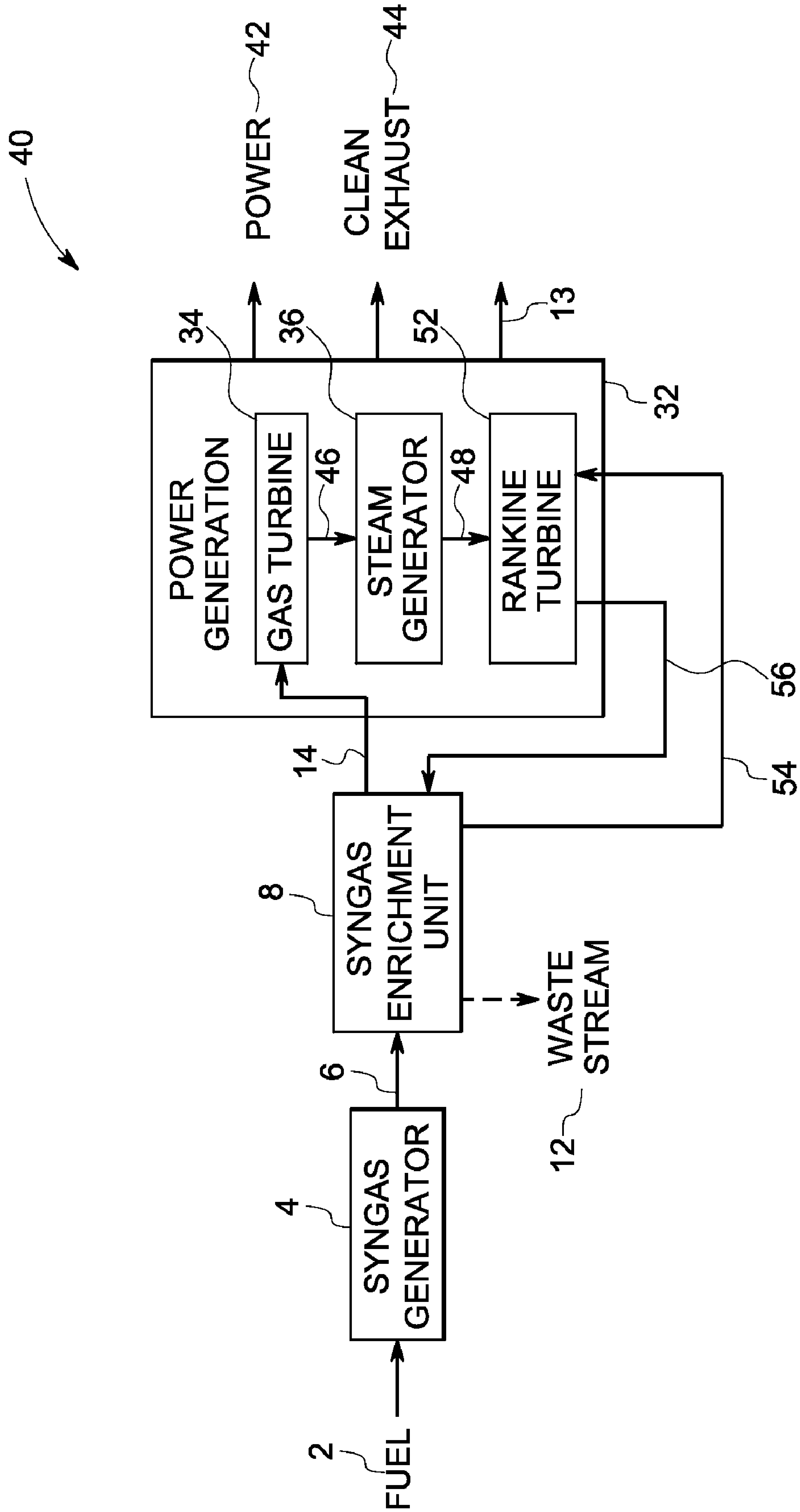
POWER
42
CLEAN
EXHAUST
44
34
36
38
POWER
GENERATION
GAS TURBINE
46
STEAM
GENERATOR
48
STEAM
TURBINE
32
28
14
SYNGAS
ENRICHMENT
UNIT
8
WASTE
STREAM
12
6
SYNGAS
GENERATOR
4
FUEL
2

FIG. 3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CLEAN EXHAUST
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POWER GENERATION
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STEAM GENERATOR
48
RANKINE TURBINE
56
14
54
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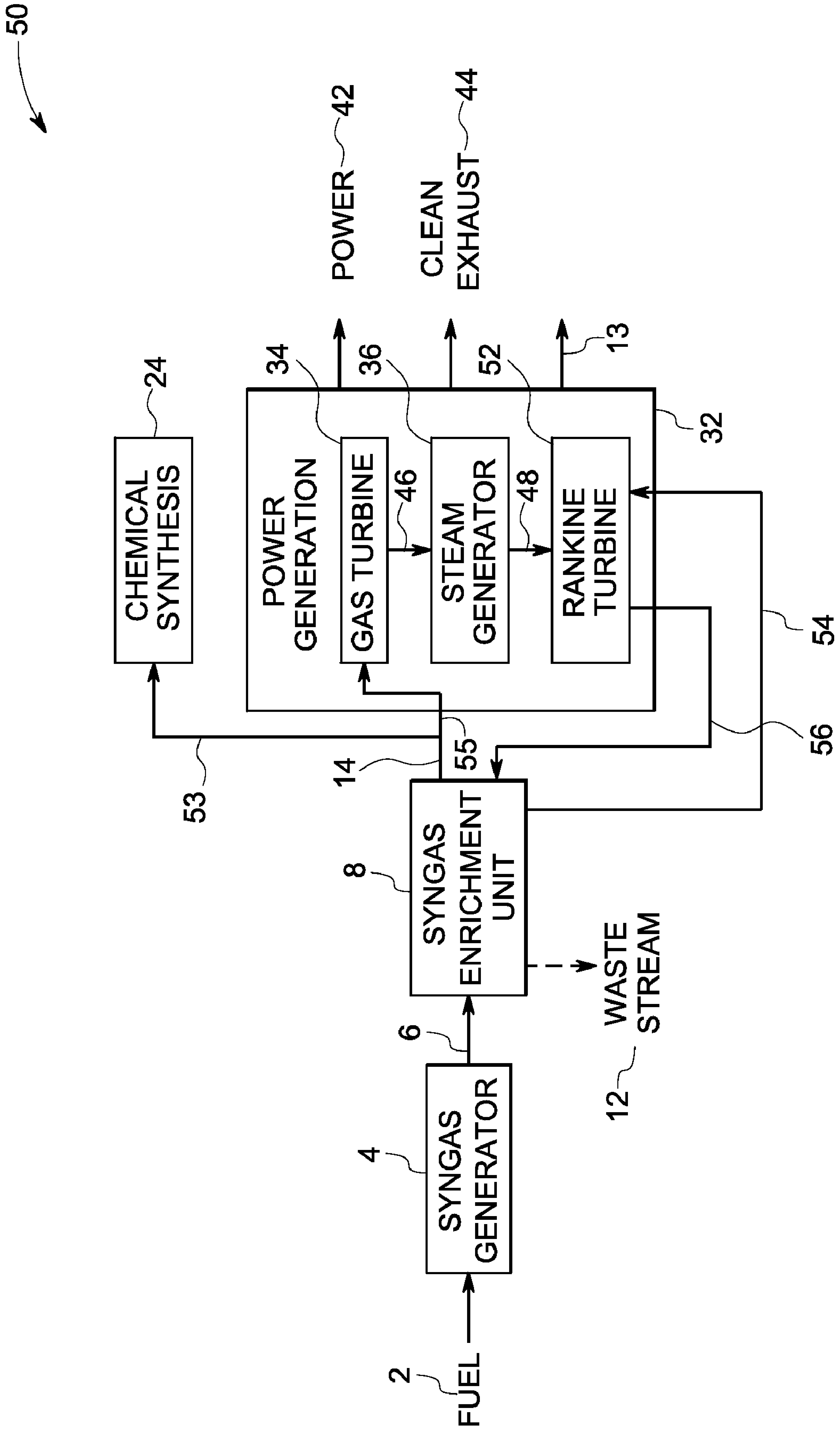
SYNGAS ENRICHMENT UNIT
WASTE STREAM
6
12
4
SYNGAS GENERATOR
2
FUEL

FIG. 4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EXHAUST
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CHEMICAL
SYNTHESIS
24
POWER
GENERATION
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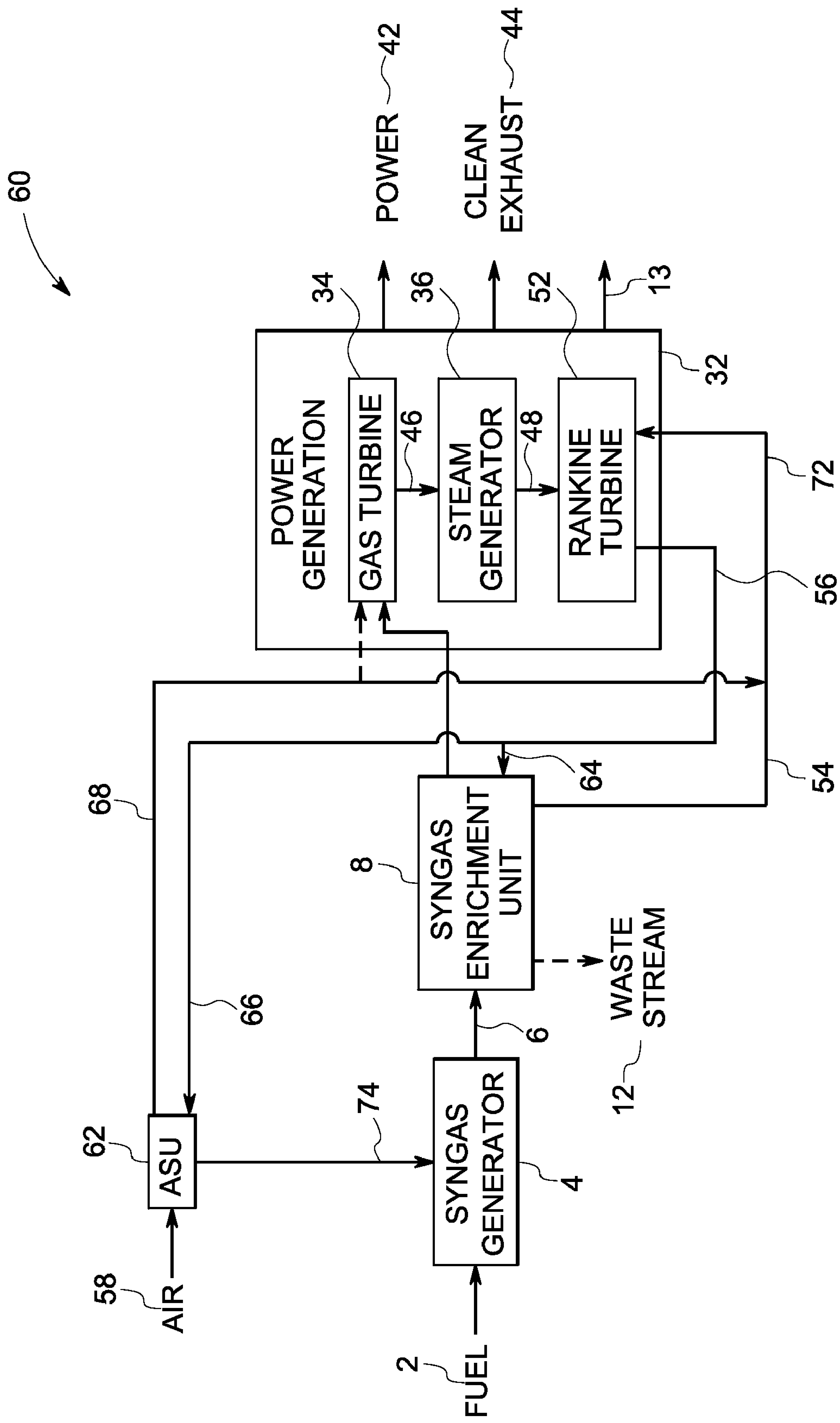
36
52
13
GAS TURBINE
46
STEAM
GENERATOR
48
RANKINE
TURBINE
32
54
56
53
14
55
SYNGAS
ENRICHMENT
UNIT
8
WASTE
STREAM
12
6
SYNGAS
GENERATOR
4
FUEL
2

FIG. 5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POWER
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CLEAN EXHAUST
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32
POWER GENERATION
GAS TURBINE
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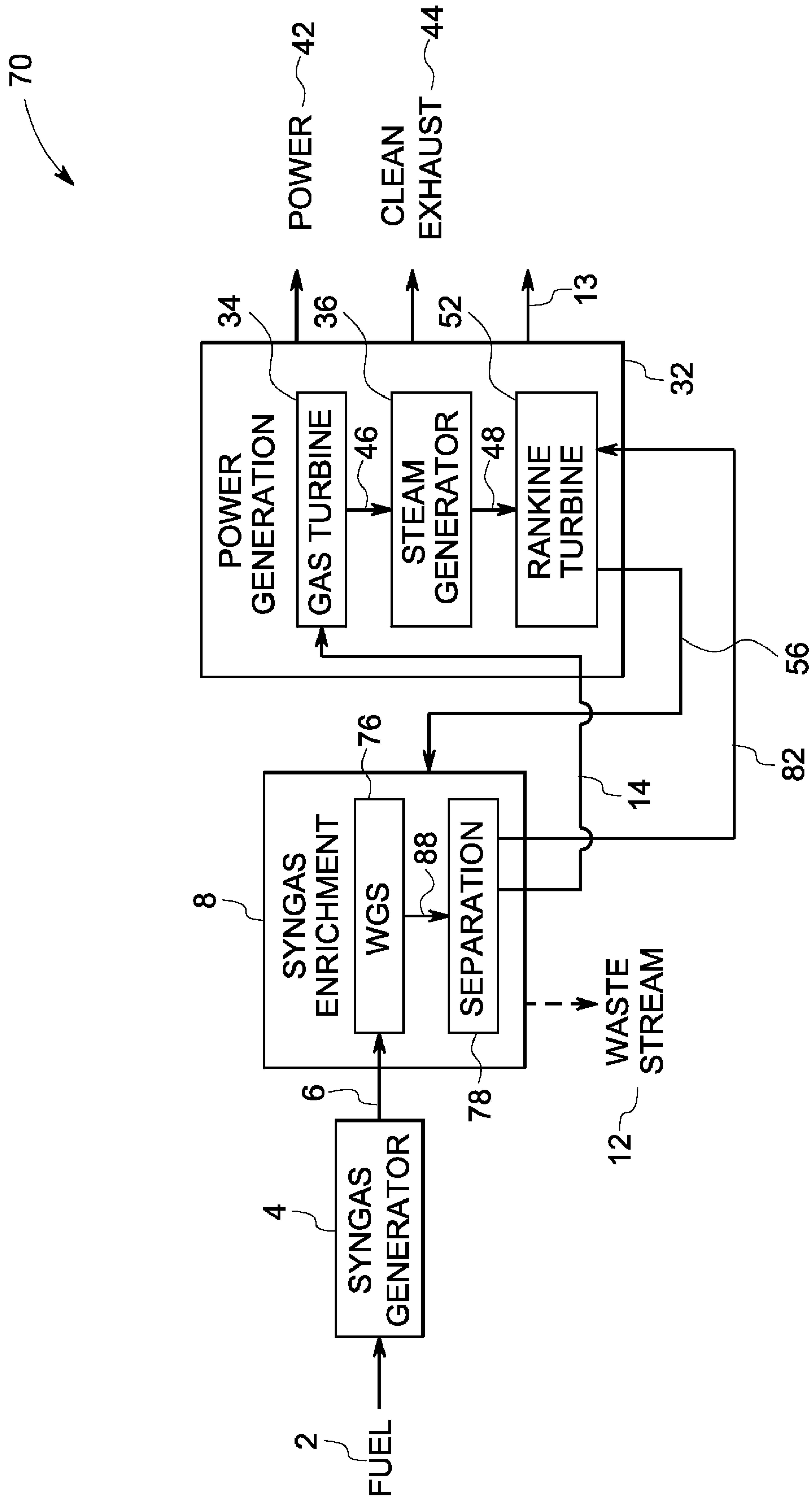
STEAM GENERATOR
48
RANKINE TURBINE
72
56
68
64
54
SYNGAS ENRICHMENT UNIT
8
WASTE STREAM
12
66
6
74
ASU
62
SYNGAS GENERATOR
4
AIR
58
FUEL
2

FIG. 6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POWER GENERATION
GAS TURBINE
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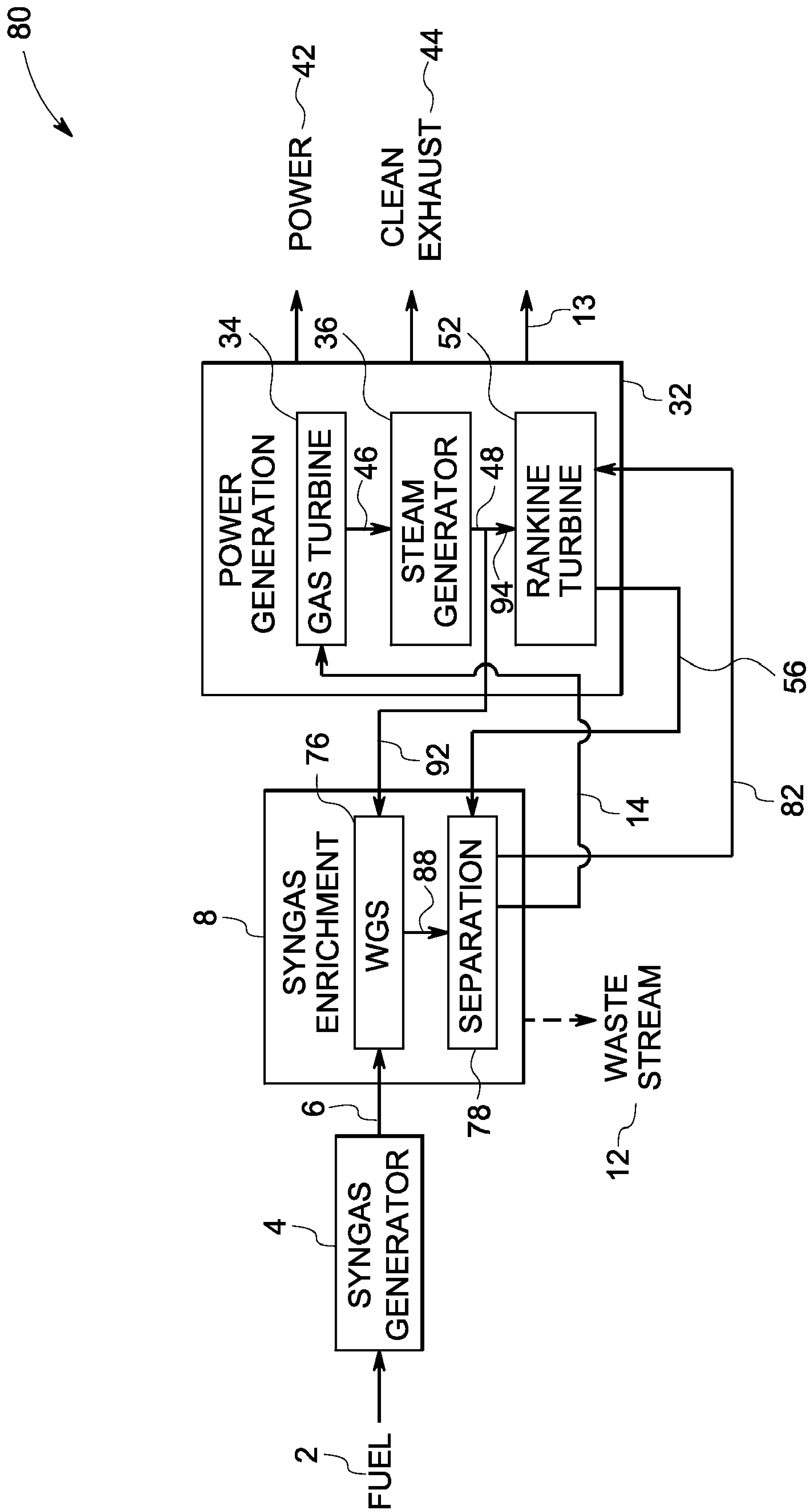
STEAM GENERATOR
48
RANKINE TURBINE
56
76
82
14
8
SYNGAS ENRICHMENT
WGS
88
SEPARATION
WASTE STREAM
6
78
12
4
SYNGAS GENERATOR
2
FUEL

FIG. 7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POWER
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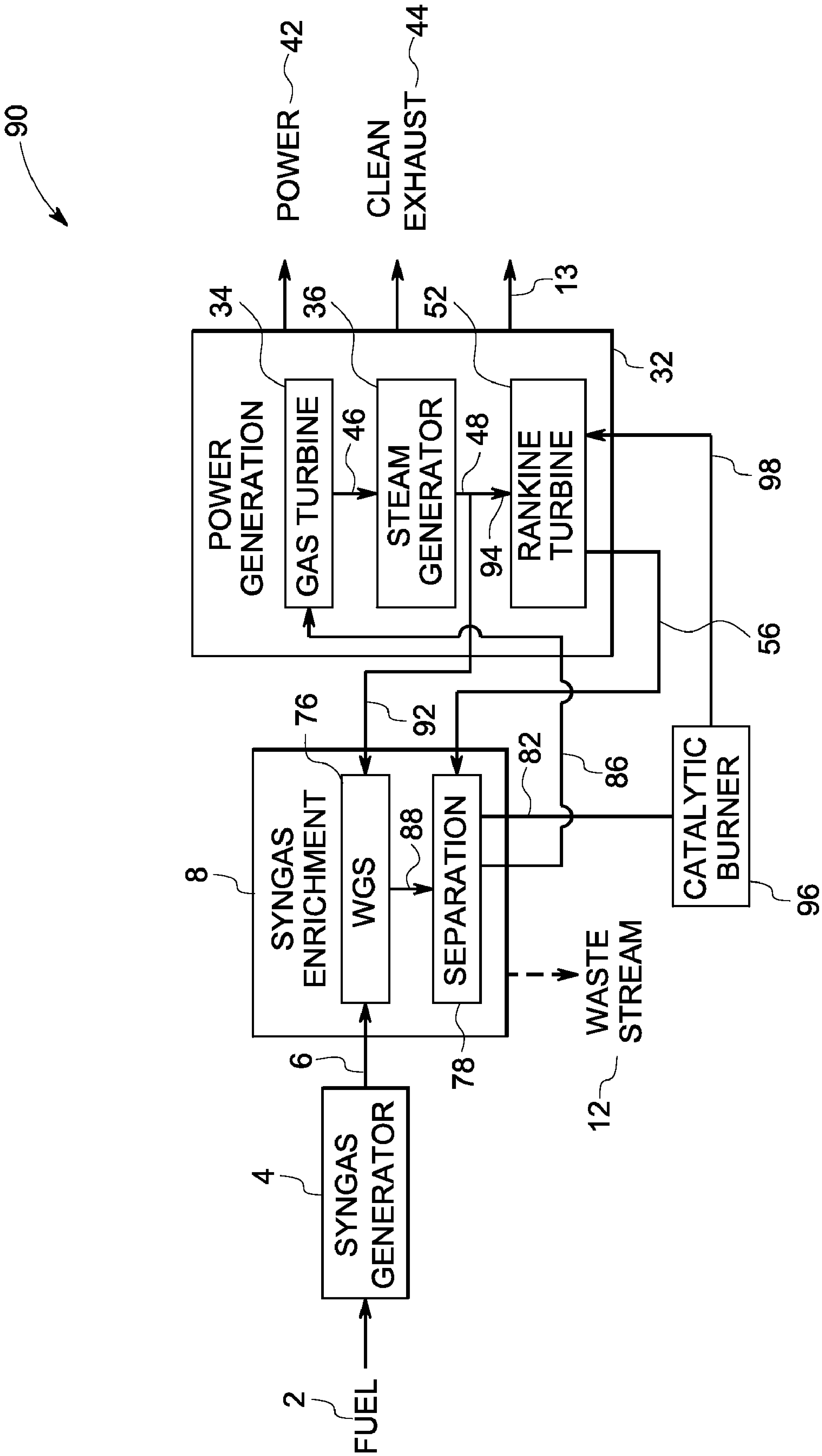
CLEAN EXHAUST
44
34
36
52
13
32
POWER GENERATION
GAS TURBINE
46
STEAM GENERATOR
48
94
RANKINE TURBINE
56
76
92
14
82
8
SYNGAS ENRICHMENT
WGS
88
SEPARATION
WASTE STREAM
6
78
12
4
SYNGAS GENERATOR
2
FUEL

FIG. 8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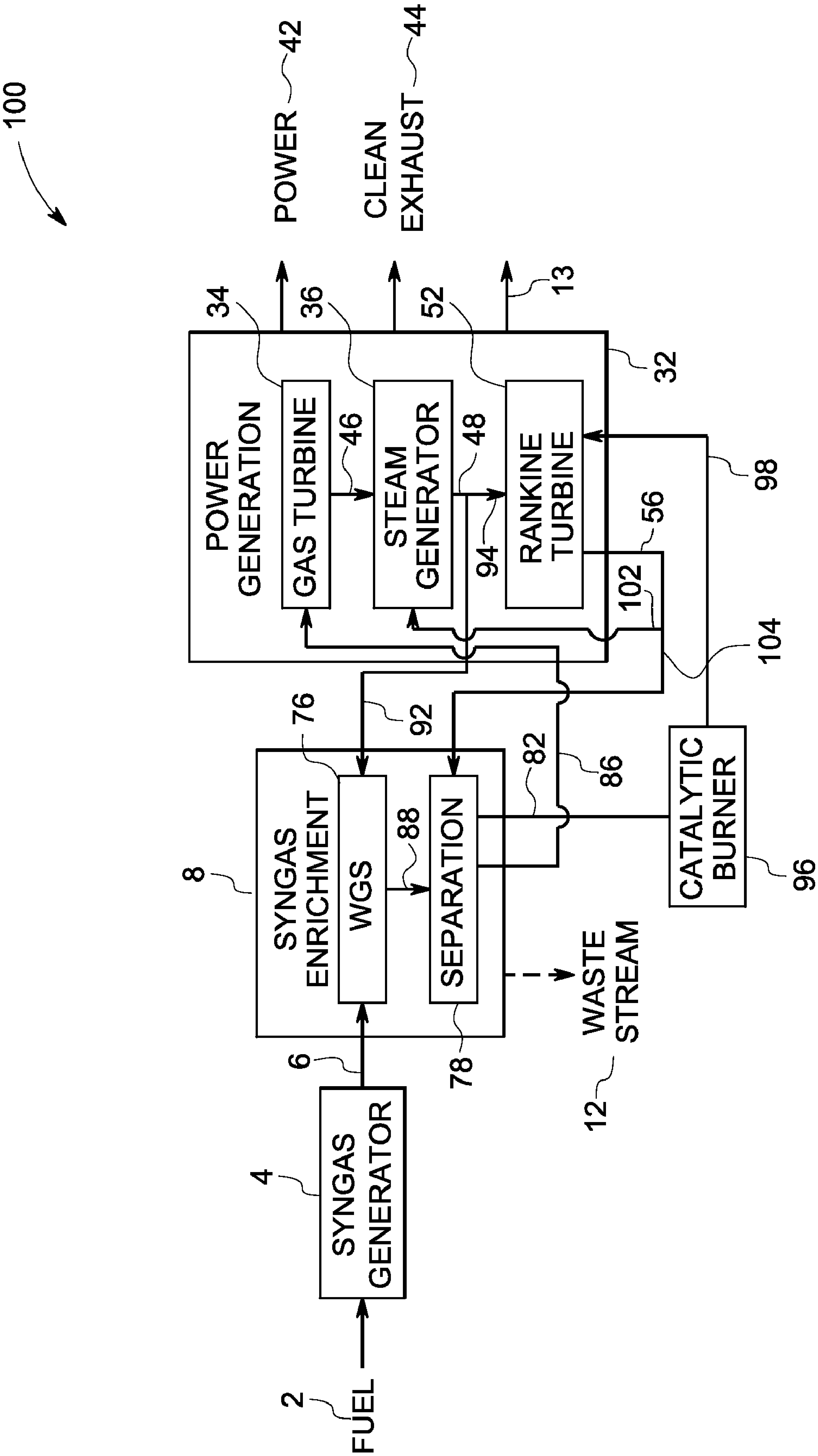
POWER
42
CLEAN EXHAUST
44
34
36
52
13
32
POWER GENERATION
GAS TURBINE
46
STEAM GENERATOR
48
RANKINE TURBINE
94
98
56
76
92
82
86
8
SYNGAS ENRICHMENT
WGS
88
SEPARATION
CATALYTIC BURNER
96
WASTE STREAM
12
78
6
4
SYNGAS GENERATOR
2
FUEL

FIG. 9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POWER
42
CLEAN EXHAUST
44
34
36
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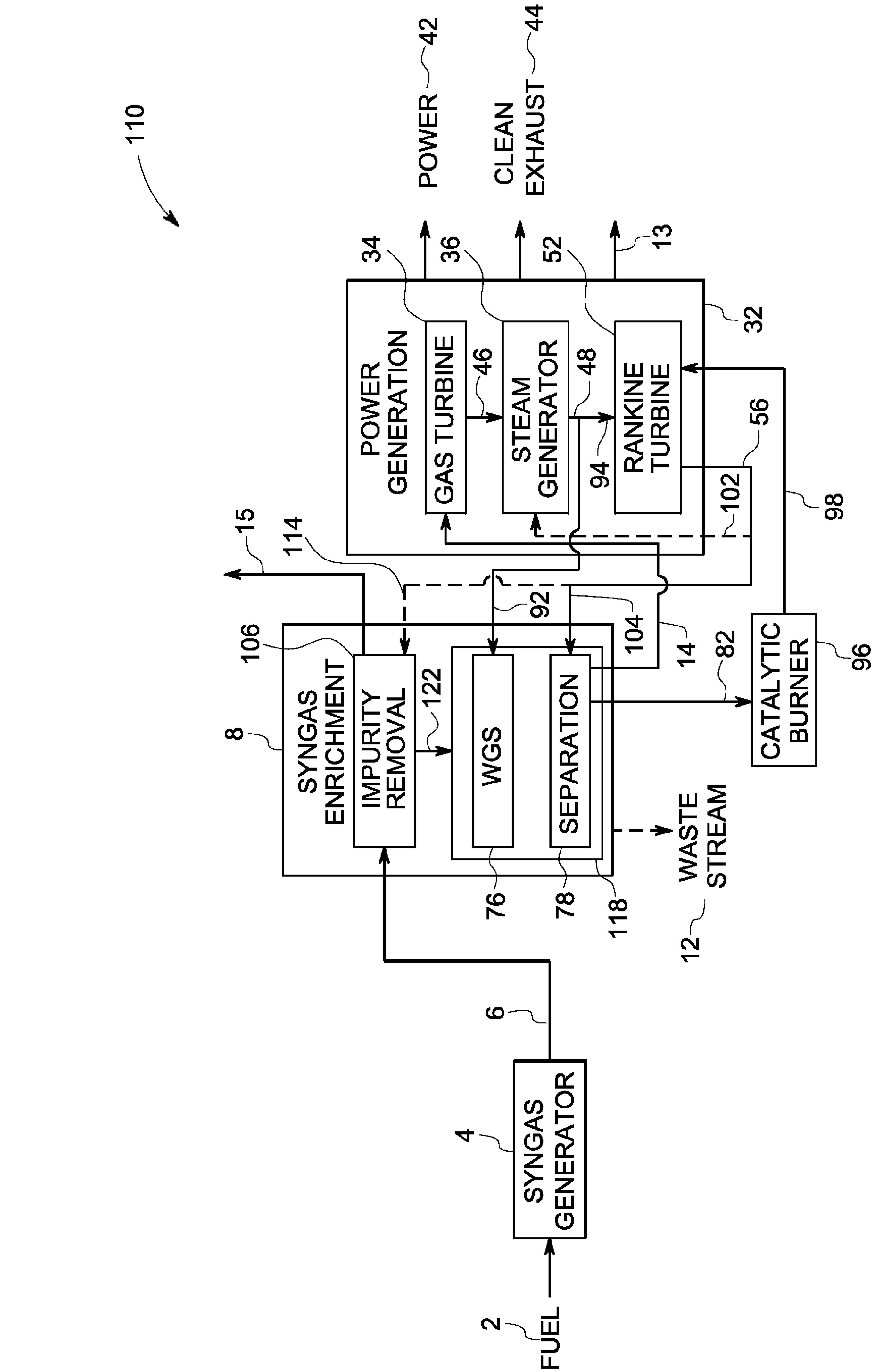
13
32
POWER GENERATION
GAS TURBINE
46
STEAM GENERATOR
48
94
RANKINE TURBINE
56
98
102
104
76
92
82
86
8
SYNGAS ENRICHMENT
WGS
88
SEPARATION
CATALYTIC BURNER
96
WASTE STREAM
12
78
6
4
SYNGAS GENERATOR
2
FUEL

FIG. 10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13
32
POWER GENERATION
GAS TURBINE
46
STEAM GENERATOR
48
94
RANKINE TURBINE
56
102
98
15
114
92
104
14
82
106
8
SYNGAS ENRICHMENT
IMPURITY REMOVAL
122
WGS
SEPARATION
CATALYTIC BURNER
96
WASTE STREAM
76
78
118
12
6
4
SYNGAS GENERATOR
2
FUEL

FIG. 11

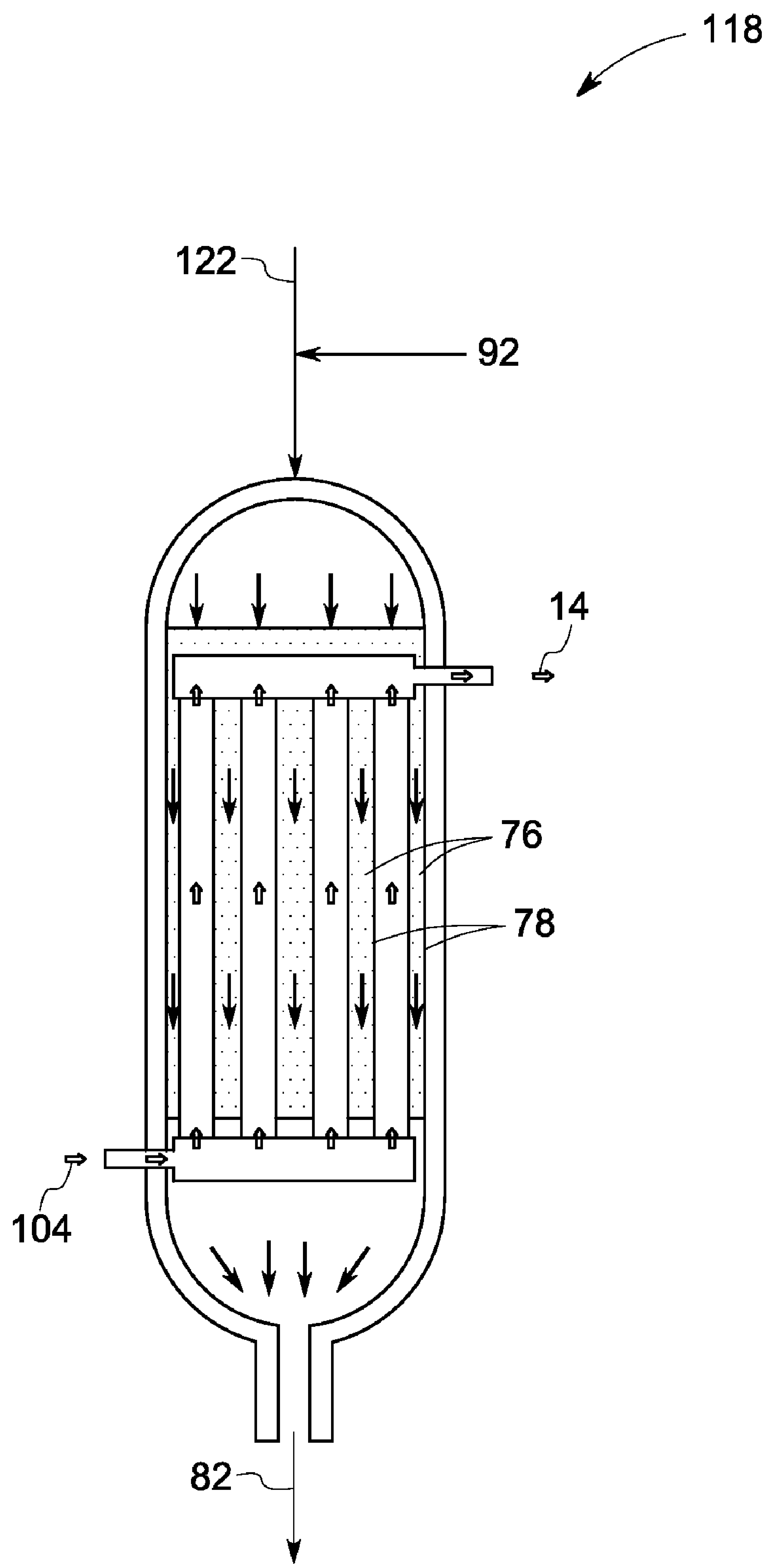
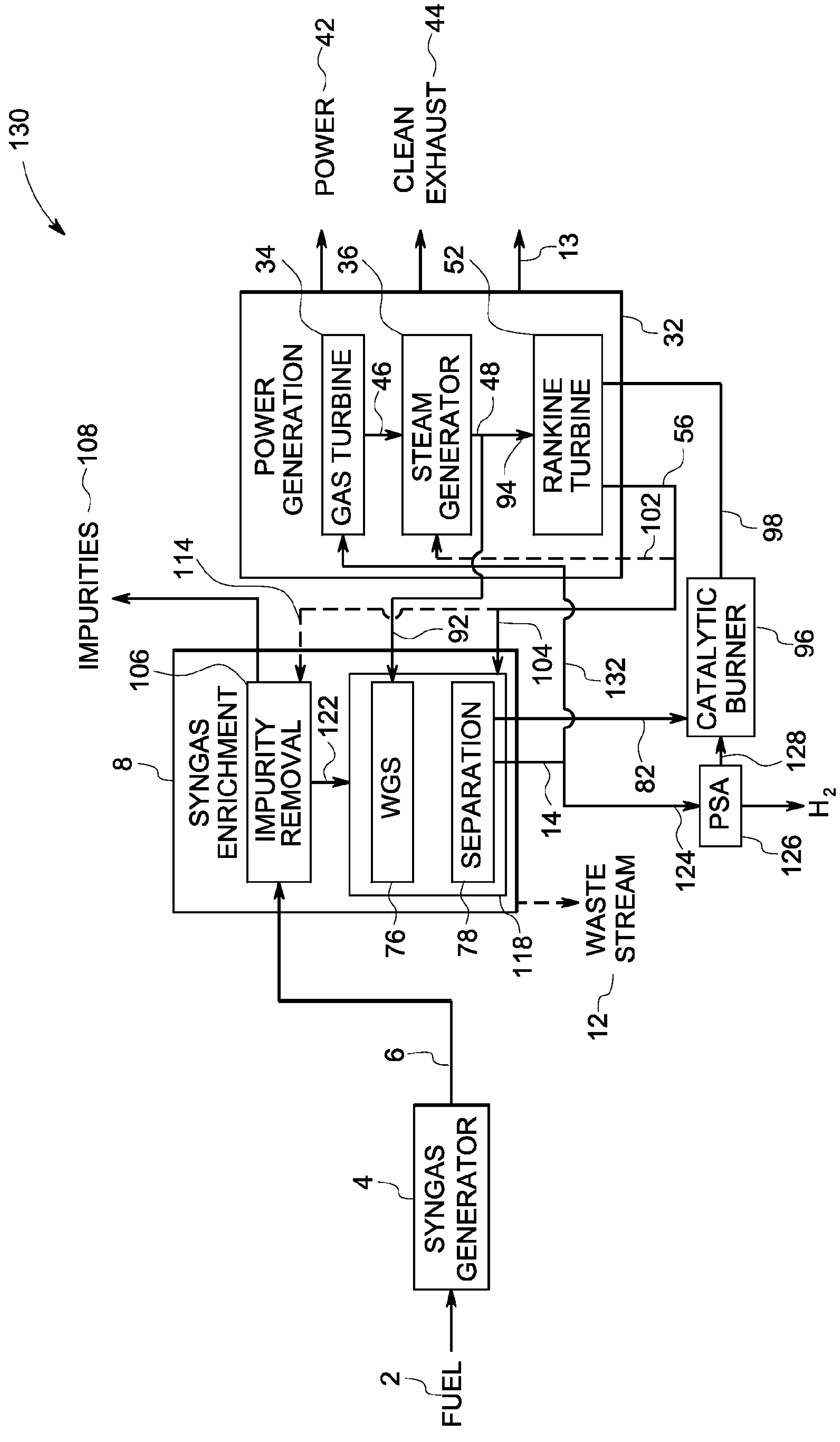


FIG. 12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FUEL
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4
6
SYNGAS ENRICHMENT
8
IMPURITY REMOVAL
106
IMPURITIES
108
114
122
WGS
76
SEPARATION
78
118
WASTE STREAM
12
92
104
132
14
82
PSA
124
126
H_2
128
CATALYTIC BURNER
96
98
POWER GENERATION
32
GAS TURBINE
34
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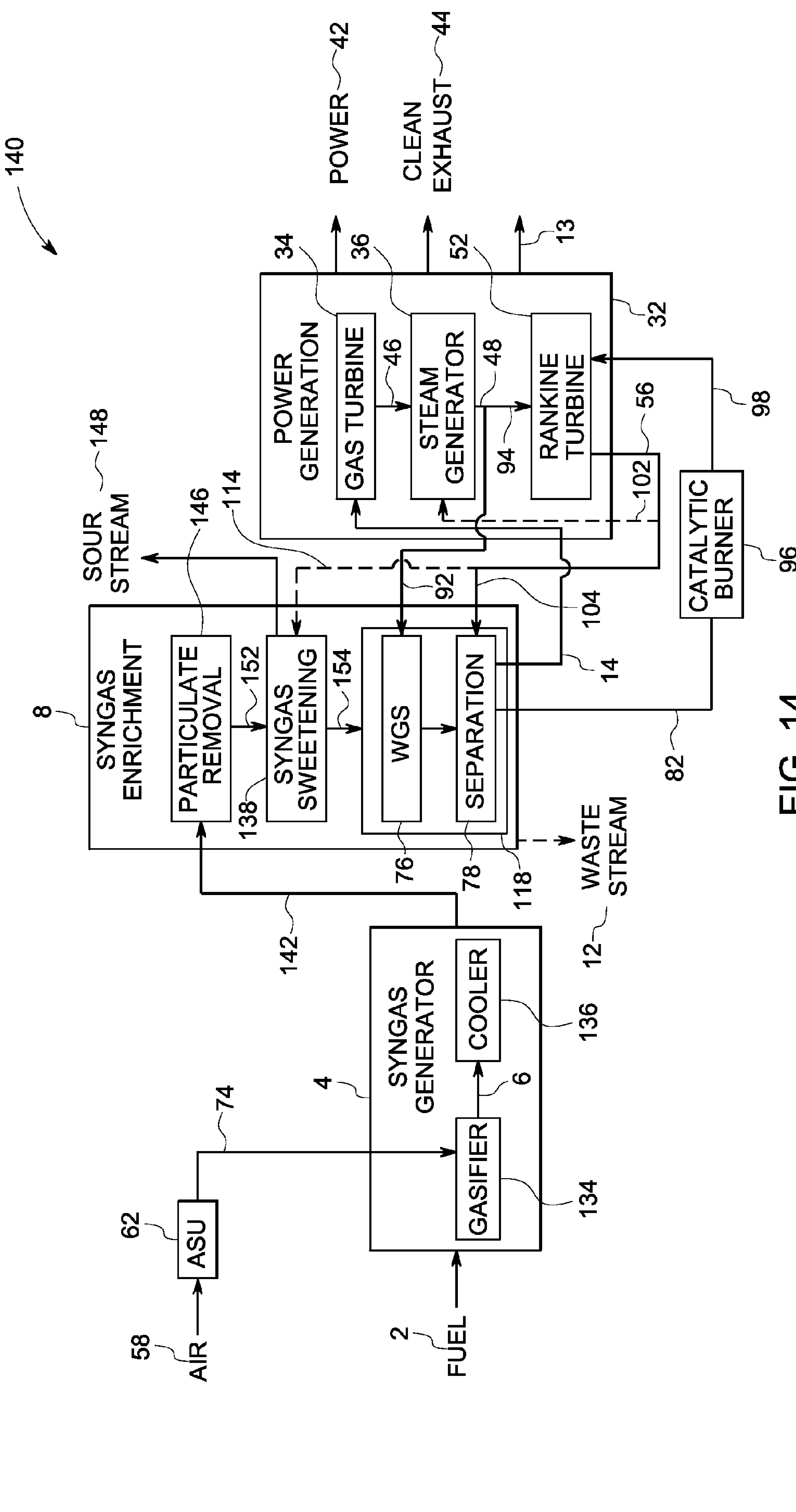
102
POWER
42
CLEAN EXHAUST
44
13

FIG. 13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GAS TURBINE
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STEAM GENERATOR
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RANKINE TURBINE
32
56
94
102
98
CATALYTIC BURNER
96
SOUR STREAM
148
146
114
92
104
14
8
SYNGAS ENRICHMENT
PARTICULATE REMOVAL
152
SYNGAS SWEETENING
154
WGS
SEPARATION
138
76
78
118
82
WASTE STREAM
12
142
SYNGAS GENERATOR
COOLER
136
4
6
GASIFIER
134
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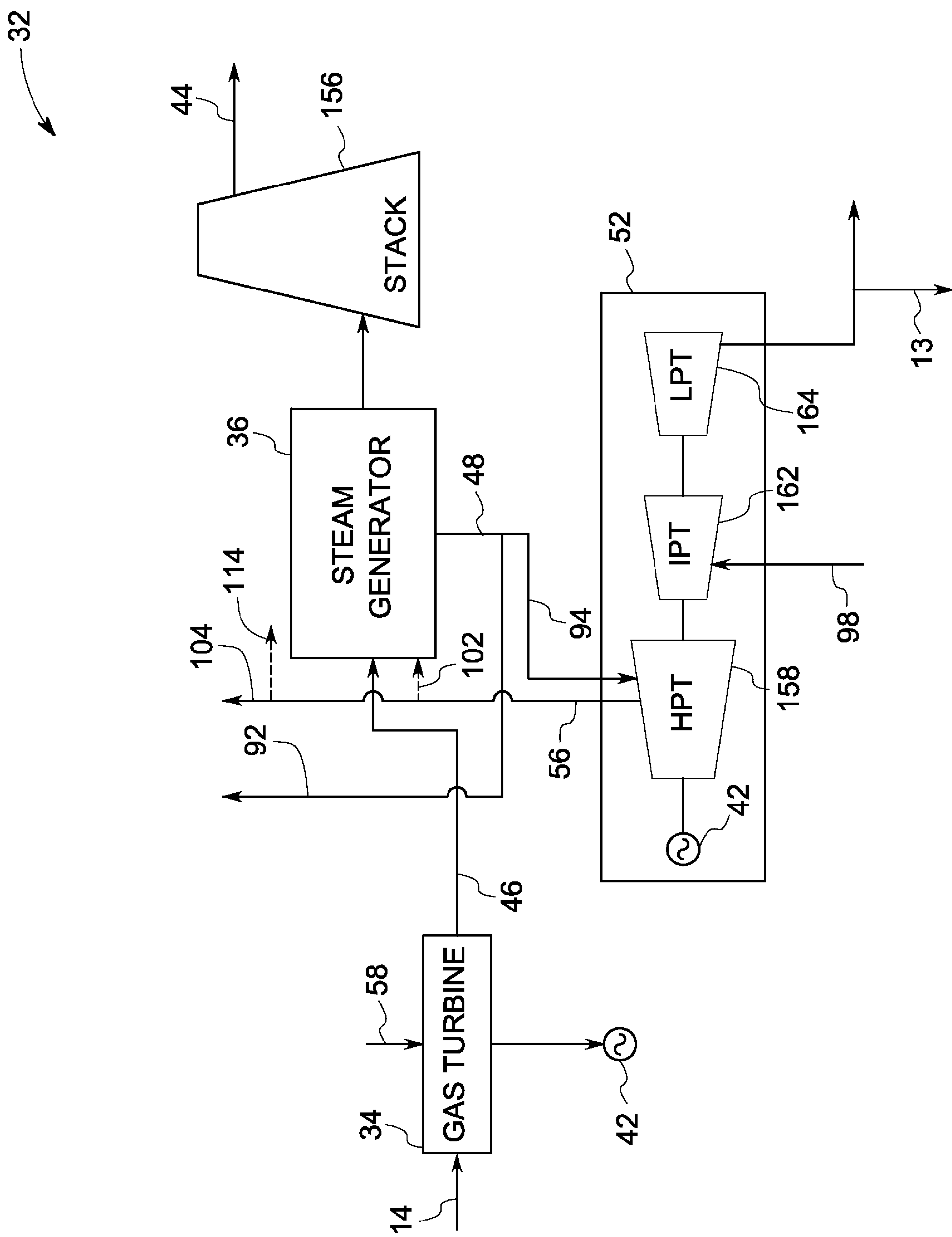
ASU
62
58
AIR
2
FUEL

FIG. 14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102
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LPT
164
IPT
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98
HPT
158
92
56
42
46
GAS TURBINE
58
34
14
42

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

$$CO+H_2O \rightarrow CO_2+H_2$$

[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

$$CO_2+C \rightarrow 2CO$$

[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 membrane 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 H_2 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 separation 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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