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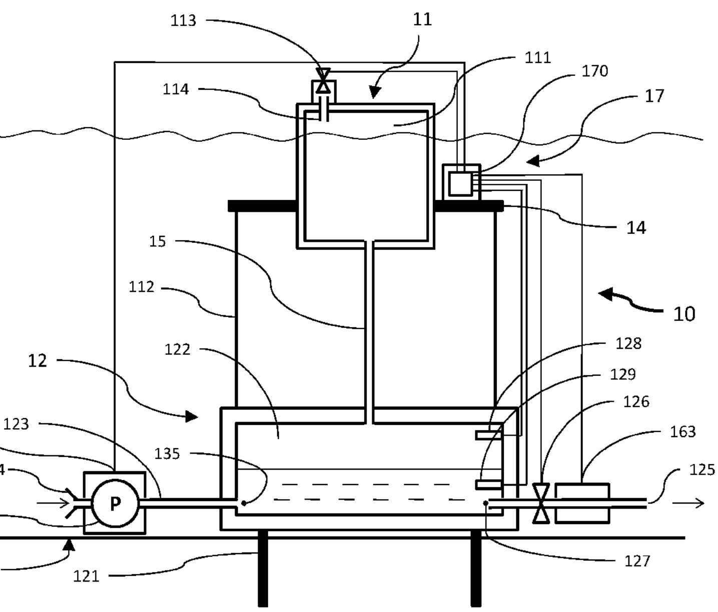
Fig. 1



(57) Abstract: A hydro-pneumatic energy storage system for deep sea water (DSW) is described. The system includes a floating support structure including a floating support platform, and a floating air chamber mounted on the floating support platform. The floating air chamber is configured for holding compressed air. The system also includes a sea-bottom mounted structure including a sea-bottom accumulator chamber configured for holding the compressed air and the DSW to store the DSW under pressure of the compressed air, and an air umbilical pneumatically interconnecting the floating air chamber with the sea-bottom accumulator chamber.

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HYDRO-PNEUMATIC ENERGY STORAGE SYSTEM

FIELD OF THE INVENTION

This invention relates to technologies generating energy,and more particularly to deep offshore floating turbine technologies with energy storage facilities.

BACKGROUND OF THE INVENTION

The world's demand for electric energy is continuously increasing. A vast amount of electric energy is currently generated by oil, gas, coal or nuclear plants. However, burning oil, gas and coal results in polluted air, and all of these fuel resources are rapidly diminishing. Nuclear energy requires the disposal of nuclear waste, which remains dangerous for centuries.

Natural energy sources are effectively inexhaustible and are abundantly available throughout the world in various forms such as natural wind, solar, tidal and wave energy. Unfortunately, natural energy sources have an irregular nature, and peak demands for electrical energy in homes and in industry are usually out of phase with the availability of natural sources of energy.

Wind energy conversion technology is today regarded as one of the most technically advanced technologies available that can effectively help develop a low carbon economy while ensuring a clean and secure supply of energy. However, wind is inherently variable. Some days are windy, some are not, and even during a single day wind varies throughout the day. Consequently, a mismatch frequently occurs between potential energy available from low winds during periods of peak demand, and high winds during periods when the demands of the electrical grid may be low, such as in the evening. Further, due to the nature of wind farms being located distant to cities requiring energy, at times the power generated in wind farms can exceed the capacity of the transmission lines communicating the power to the grid requiring it. Unable to transmit the power generated during peak winds, frequently wind farms will idle turbines which could be producing electrical energy at a maximum rate.

Similarly, solar energy is most abundant typically during the middle of the day, however, solar cells generate no electricity at night. Additionally, solar energy farms are frequently located at a significant distance from the power grids they serve, and transmission lines can limit the amount of power that may be transmitted from the solar power farm to the distant grid. If transmission lines lack the capacity to transmit the full amount of power of a solar power farm produced at midday, the energy will have to be shed and wasted.

Likewise, tidal and wave power does not often coincide with the times of peak electrical energy demand.

Accordingly, it is necessary that the energy obtained from natural energy sources be somehow stored so as to be releasable during periods of power demand, as required.

A variety of techniques are available to store excess power for later delivery. One approach to energy storage is the use of batteries. Large storage batteries have been developed on a commercial basis and have been used both on farms and in industry. Electrical storage batteries, however, are objectionable due to problems relating to durability and maintenance. Moreover, many large-scale batteries use a lead electrode and acid electrolyte, and these components are environmentally hazardous.

Energy can also be stored in ultracapacitors. A capacitor is charged by line current so that it stores charge, which can be discharged rapidly when needed. Appropriate power-conditioning circuits are used to convert the power into the appropriate phase and frequency of AC. However, a large array of such capacitors is needed to store a substantial amount of electrical energy. Ultracapacitors, while being more environmentally friendly and lasting longer than batteries, are substantially more expensive, and still require periodic replacement due to the breakdown of internal dielectrics, etc.

Pumped hydro and compressed air systems are known in the art. For example, U.S. Pat. No. 4,010,614 describes a system for converting natural energy into usable electricity. The system includes an elevated reservoir for the storage of excess energy. A solar collector produces steam to drive an electrical generator and a hydraulic pump. When the demand for electrical energy is below the capacity of the generator, the excess energy is used to drive the hydraulic pump. Water is transported by the hydraulic pump from a low level reservoir to the elevated reservoir to thereby store potential energy. When demand increases beyond the capacity of the generator or when the supply of solar energy is decreased sufficiently, water from the elevated reservoir is used to drive a second electrical generator.

U.S. Pat. No. 4,058,070 describes a system utilizing kinetic energy of the wind that is converted into compressed air which is stored, in the system, at a predetermined output pressure. The compressed air is used for driving a turbine coupled to an electrical power generator.

U.S. Pat. No. 4,206,608 describes an apparatus and method for utilizing natural energy in the production of electricity. The natural energy obtained from a plurality of natural energy sources is utilized to pressurize hydraulic fluid. A plurality of natural energy sources are used so that periodic and intermittent fluctuations in the supply of natural energy of one particular form may be compensated for by the other forms of natural energy. The pressurized hydraulic fluid is supplied to a pressure storage tank wherein a compressible fluid is compressed by the pressurized hydraulic fluid. Electrical energy is produced by the pressurized hydraulic fluid and is supplied as needed to various consumers. Excess electricity which is not needed by consumers is supplied to an electric motor which drives a hydraulic pump. The excess energy is thereby utilized to pressurize hydraulic fluid which is supplied to the high pressure storage tanks. In this way, excess energy is conserved and is not wasted needlessly.

U.S. Pat. No. 7,239,035 describes an integrated, wind-pumped hydro power generation system that includes at least one wind turbine generator device configured to generate output power for a common bus, and at least one hydro generator device configured to generate output power for the common bus. The hydro generator device is powered by water flow. The wind turbine generator device and the hydro generator device include corresponding local controls associated therewith, and a set of supervisory controls is in communication with the common bus and each of the local controls.

Exisiting commercial offshore wind farms are based on seabed-mounted foundations technology to support wind turbines that are only suited for shallow waters typically at depths usually not exceeding 50 meters. Floating offshore wind technologies enable the exploitation of untapped wind resources at deep water sites further away from the coast where marine wind energy resources are more abundant and continuous than those on shore. Moreover, issues related to visual, noise and ecological impacts, as well as potential conflicts with shipping, aviation and coastal surveillance are expected to be of a lesser concern.

For example, U.S. Pat. No. 8,169,099 describes a deep off-shore floating wind turbine apparatus and methods of manufacturing, operating, maintaining, protecting and conveying the wind turbine apparatus. The wind turbine includes a rotor converting a motion of air into a movement of the rotor, a hub housing equipment that transforms the movement of the rotor into a useful form of energy, and a tower supporting the hub on one end. The wind turbine further includes a base floating substantially at the water surface and movable with respect to the underlying solid surface. The tower is connected to the floating base on the second end. The wind turbine also includes a tilting mechanism tilting the wind turbine into a substantially horizontal orientation and bringing it back into an upright position, as well as a rotating mechanism operable to control azimuth orientation of the wind turbine.

U.S. Pat. No. 8,662,793 describes a floating wind farm that includes a plurality of floating rafts connected with one another and disposed in a body of water below the water by a predetermined distance. A plurality of wind turbines are connected to the floating rafts respectively and configured to be driven by wind and thereby generate power. A power generator is connected to the floating rafts. A plurality of anchors are connected to the floating rafts respectively and disposed in the water for confining the location of the floating rafts. Each of the floating rafts includes at least three pipes and a plurality of ballast blocks attached to the pipes. The pipes are configured to store air compressed by the power generated by the wind turbines. The power generator is configured to generate and output electricity from the compressed air stored in the pipes.

GENERAL DESCRIPTION OF THE INVENTION

The concept of the invention involves storage of pressurised cold deep sea water, enabling the concurrent exploitation of wind, solar, tidal and wave energy and thermal energy available in deep sea while mitigating problems originating from intermittency in natural energy sources.

Offshore wind, wave and tidal turbine technologies are usually based on systems in which a rotor of a wind, wave or tidal turbine drives an electrical generator that converts the rotational mechanical energy into electricity, which is then transported to shore via an electrical infrastructure consisting of cables and a transformer station. However, renewable energy from existing offshore turbine technologies in which the wind, wave or tidal turbine is associated with an electrical power generator is expensive at offshore sites located in relatively deep areas, and especially where wind speeds or wave and tidal currents are low. Moreover, when the electric energy is directly generated by the wind, wave and tidal turbines, this energy cannot be effectively stored so as to be dispatched during periods of power demand, as required. Integration of deep offshore floating turbine technologies with energy storage facilities can mitigate problems associated with the intermittent supply of natural energy by providing a regulated supply of pressurized deep sea water. Potential energy of pressurized deep sea water can, for example, be converted into electricity by allowing the pressurized deep sea water to flow through a hydraulic turbine connected to an electric generator.

Furthermore, deep water sites provide an immense resource of renewable thermal energy that can be used for cooling or heating applications. This resource is driven by thermocline phenomena whereby the seawater experiences thermal stratification with the water temperature decreasing with depth for most of the year. This is a consequence of the fact that the upper sea layers are more exposed to absorb solar radiation than the lower ones. At greater depth limits, the temperature gradients are no longer evident and the temperature reaches a stable level, independent of season. This variation of temperature with sea depth may be divided into three distinct zones: the mixed upper layer, the thermocline, where rapid variations in temperature occur, and the deep sea layer where a stable temperature is reached. The temperature of deep sea water may be considerably higher or lower than the ambient air temperatures in urban areas for most of the year, thereby providing potential for cooling or heating of buildings. One should take note of the fact that there exist significant populations living in coastal locations adjacent to deep bodies of water. An appreciable portion of these locations have substantial cooling demands. Moreover, large-scale plants demanding large amounts of energy for cooling (e.g., natural gas liquefication plants) are also located at the coast. There is thus a need in the art for, and it would be useful to explore the possibility of utilizing offshore natural power farms located at deep water sites in order to extract deep sea water and store it at high pressure.

It would be useful to have a hydro-pneumatic energy storage system located at deep water sites that can store pressurized sea water and enable transportation of the pressurized sea water to shore for the purposes of generating electricity and cooling. For example, rather than producing electricity directly, the individual wind, tidal, wave turbines would pump sea water under high pressure to a centralized hydro-electric station for generating electricity and for cooling in buildings and industrial processes. This can result in reducing the cost of renewable energy from offshore wind, tidal and wave and solar farms.

The present disclosure satisfies the aforementioned need by providing a novel hydro-pneumatic energy storage system for deep sea water (DSW).

The system includes a floating support structure including a floating support platform and a floating air chamber. The floating air chamber is mounted on the floating support platform and is configured for holding compressed air. The system also includes a sea-bottom mounted structure including a sea-bottom accumulator chamber. The sea-bottom accumulator chamber is configured for holding compressed air and the DSW to store the DSW under pressure of the compressed air.

The floating air chamber and the sea-bottom accumulator chamber are pneumatically interconnected with an air umbilical. The air umbilical includes an air conduit configured to provide a pneumatic communication for linking the compressed air of the floating air chamber with the compressed air of the sea-bottom accumulator chamber.

According to an embodiment of the present invention, the sea-bottom mounted structure includes a sea water inlet pipeline passing from a DSW region to the sea-bottom accumulator chamber and is hydraulically coupled to an inlet port of the sea-bottom accumulator chamber, and an outlet pipeline coupled to the sea-bottom accumulator chamber configured to discharge the DSW egress flow.

According to an embodiment of the present invention, the floating air chamber has a volume sufficient for the compressed air in the air chamber to provide necessary buoyant force to the floating support platform.

According to an embodiment of the present invention, the hydro-pneumatic energy storage system includes a set of mooring lines configured for anchoring the floating support structure. According to one example, the floating support structure is anchored to the sea-bottom mounted structure. According to another example, the floating support structure is anchored to a sea-bed.

According to one embodiment of the present invention, the sea-bottom mounted structure is rigidly fixed to a sea-bed by driven piles inserted in the sea-bed.

According to another embodiment of the present invention, the sea-bottom mounted structure is rigidly fixed to the sea-bed through a gravity-based system.

According to an embodiment of the present invention, the floating support structure includes a pneumatic control valve pneumatically connected to the floating air chamber, and configured to pressurize the hydro-pneumatic energy storage system with compressed air.

According to an embodiment of the present invention, the sea-bottom mounted structure includes an outlet hydraulic control valve arranged in the outlet pipeline and configured to regulate the DSW egress flow from the sea-bottom accumulator chamber.

According to an embodiment of the present invention, the hydro-pneumatic energy storage system includes a control system coupled to the pneumatic control valve and to the hydraulic control valve for controlling operation thereof.

According to an embodiment of the present invention, the control system includes at least one pneumatic pressure sensor, at least one hydraulic pressure sensor, two water level sensors, at least one flow meter, and an electronic controller operatively coupled to said at least one pneumatic pressure sensor, said at least one hydraulic pressure sensor and said at least one flow meter.

The pneumatic pressure sensors are configured for producing air pressure sensor signals representative of the air pressure in the floating air chamber and/or the sea-bottom accumulator chamber. The hydraulic pressure sensors are configured for producing hydraulic pressure sensor signals representative of the DSW pressure within the sea water inlet pipeline and/or within the outlet pipeline. The water level sensors can be arranged inside the sea bottom mounted structure and configured for producing minimal and maximal DSW level signals to ensure that the level of DSW inside the sea-bottom accumulator chamber is within a predetermined level limit range.

The flow meters can for example be arranged within the sea water inlet pipeline and within the outlet pipeline, and can be configured for producing DSW flow sensor signals representative of the DSW flow within the sea water inlet pipeline and within the outlet pipeline. The electronic controller is responsive to the air pressure sensor signals, the hydraulic pressure sensor signals and the DSW flow sensor signals. The electronic controller is, *inter alia*, capable of generating control signals for controlling the operation of the pneumatic control valve and the hydraulic control valve.

According to an embodiment of the present invention, the hydro-pneumatic energy storage system includes a compression system arranged within the sea water inlet pipeline. The compression system includes a pump configured for pumping the DSW through the sea water inlet pipeline to the sea-bottom accumulator chamber for storing the DSW at a predetermined pressure.

According to an embodiment of the present invention, the hydro-pneumatic energy storage system further includes a prime mover engaged with the compression system and configured to drive the pump.

According to one embodiment of the present invention, the pump of the compression system is an electric pump that is coupled to an electrical power grid and powered by electricity. According to this embodiment, the prime mover can include at least one renewable energy system configured to generate output electrical power and provide it to the grid. The renewable energy system can be selected from an electrical wind turbine system, an electrical tidal turbine system, an electrical sea wave turbine system and an electrical solar system.

According to one example, the prime mover includes an electrical wind turbine system. The electrical wind turbine system includes a rotor driven by wind, a plurality of wind vanes disposed on the rotor and configured to intercept prevailing winds, and an electrical generator operatively engaged with the rotor and connected to the electrical power grid. The electrical generator is configured to generate output electrical power and provide it to the grid.

According to another example, the prime mover includes an electrical tidal turbine system. The electrical tidal turbine system includes a rotor driven by tidal current, a plurality of wind vanes disposed on the rotor and configured to intercept prevailing tidal current, and an electrical generator operatively engaged with the rotor and connected to the electrical power grid. The electrical generator is configured to generate output electrical power and provide it to the grid.

It should be noted that when the prime mover includes an electrical turbine system (either a wind turbine system or a tidal turbine system), the pump consumes electricity from the grid in order to pump deep sea water under pressure into the energy storage system.

According to another embodiment of the present invention, the pump of the compression system is a hydraulic pump. The prime mover includes at least one renewable energy system mechanically coupled to said hydraulic pump for driving thereof, said at least one renewable energy system selected from a hydraulic wind turbine system, a hydraulic sea wave turbine system and a hydraulic tidal turbine system.

According to one example, the prime mover includes a hydraulic wind turbine system. The hydraulic wind turbine system includes a rotor driven by wind and mechanically coupled to the hydraulic pump, and a plurality of wind vanes disposed on the rotor and configured to intercept prevailing winds.

According to another example, the prime mover includes a hydraulic tidal turbine system. The hydraulic tidal turbine system includes a rotor driven by tidal current and mechanically coupled to said hydraulic pump for driving thereof, and a plurality of vanes disposed on the rotor and configured to intercept prevailing tidal current.

According to one general aspect of the present invention, there is provided a hydro-pneumatic energy storage assembly comprising a plurality of the hydro-pneumatic energy storage systems described above arranged in series and interconnected through sea water pipelines.

According to one general aspect of the present invention, there is provided a hydro-pneumatic energy storage assembly comprising a plurality of floating support structures interconnected with a plurality of sea-bottom mounted structures through deep sea water pipelines and through pneumatic pipelines. The sea-bottom mounted structures are arranged in series and are interconnected through sea water pipelines, wherein the floating air chamber of each floating support structure is interconnected with the sea-bottom accumulator chambers of two neighboring sea-bottom mounted structures through pneumatic pipelines.

The energy storage system of the present invention has many of the advantages of the prior art techniques, while simultaneously overcoming some of the disadvantages normally associated therewith.

The proposed integration of an energy storage system in floating support structures in deep waters allows for storage of cold pressurized deep sea water, making it possible to concurrently store energy received from natural energy sources in two forms, such as: (i) potential energy, which may be converted to electricity by allowing the pressurized deep sea water to flow through a hydraulic turbine connected to an electric generator; and (ii) thermal renewable energy suitable for cooling purposes.

The concept of having wind turbines pump pressurized sea water directly, in lieu of generating electricity, is expected to offer some other important advantages in offshore wind exploitation: it would facilitate the integration of wind, solar, tidal and/or wave power with wave power extracting devices, energy storage systems and reverse osmosis desalination plants. It would also reduce the need for copper and rare earth materials. Apart from potentially reducing costs by minimizing the use of copper and rare earth materials required for electrical systems, this approach can facilitate the integration of wind, solar, tidal and/or wave farms with hydro-energy storage systems, thus mitigating problems associated with grid congestion and stability.

An additional advantage of the energy storage system herein disclosed is that it enables mitigating problems associated with the unreliable intermittent supply of natural energy by providing a regulated supply of pressurized and cold deep sea water.

A further advantage of the energy storage system herein disclosed is that it may be continually upgraded to be sized as needed, which is effective for both long term and short term energy storage.

The hydro-pneumatic energy storage system of the present invention only requires minimal moving parts. Unlike other energy storage technologies such as batteries, the system has a long service lifetime and its performance does not degrade with the number of energy storage cycles. Furthermore, the utilized materials are mainly limited to steel/concrete.

By utilizing hydraulic wind, wave and tidal turbines providing a directly pressurized supply of DSW, energy is stored in the form generated, hence reducing losses associated with energy storage.

The storage of pressurized DSW at the sea-bed rather than in the upper floating support structure, ensures that floating stability is not influenced by energy storage operations and that the stored DSW will not get warmer but rather retain the fixed sea bottom temperature.

The compressed air chamber on the floating support platform can be easily accessible for pressurization/de-pressurization during installation and maintainance through a valve located at the upper floating support structure.

The hydro-pneumatic energy storage system of the present invention allows for a more pressure stable hydraulic network due to maximizing the use of volume for compressed air by using the volume of the upper floating structure. This provision may further facilitate the integration of offshore wind farms with other intermittent marine renewable energy technologies (such as wave and sea current energy) as well as desalination plants relying on reverse osmosis technologies.

The integration of the proposed hydraulic-based storage system allows for the installation of smaller (hence cheaper) diameter pipelines in wind, wave and tidal farms based on hydraulic power transmission.

The commercialization of floating offshore wind technologies in the near future will open endless opportunities to develop large offshore wind farms capable of meeting a considerable share of energy demand. Yet, technical problems originating from intermittency in the wind and other natural energy sources are regarded as major obstacles for the integration of large offshore natural sources into national grids. The integration of energy storage systems is therefore considered as a crucial development to facilitate the exploitation of power of natural energy sources on a wide scale. Minimizing the energy storage costs by optimizing energy storage efficiencies and minimizing the additional infrastructural costs required is critical to maintain wind energy production within feasible limits.

There has thus been outlined, rather broadly, the more important features of the invention in order that the detailed description thereof that follows hereinafter may be better understood. Additional details and advantages of the invention will be set forth in the detailed description, and in part will be appreciated from the description, or may be learned by practice of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic cross-sectional view of a hydro-pneumatic energy storage system, according to one embodiment of the present invention;

Fig. 2 is a schematic cross-sectional view of a hydro-pneumatic energy storage assembly, according to an embodiment of the present invention;

Fig. 3 is a schematic cross-sectional view of a hydro-pneumatic energy storage assembly, according to another embodiment of the present invention;

Fig. 4 is a schematic cross-sectional view of the hydro-pneumatic energy storage system connected to an electricity grid network, according to an embodiment of the present invention;

Fig. 5 is a schematic cross-sectional view of the hydro-pneumatic energy storage system configured to utilize wind energy for providing and storing pressurized DSW, according to an embodiment of the present invention;

Fig. 6 is a schematic cross-sectional view of the hydro-pneumatic energy storage system configured to utilize wind energy for providing and storing pressurized DSW, according to another embodiment of the present invention;

Fig. 7 is a schematic cross-sectional view of the hydro-pneumatic energy storage system configured to utilize tidal energy for providing and storing pressurized DSW, according to an embodiment of the present invention;

Fig. 8 is a schematic cross-sectional view of the hydro-pneumatic energy storage system configured to utilize tidal energy for providing and storing pressurized DSW, according to another embodiment of the present invention;

Fig. 9 is a schematic cross-sectional view of the hydro-pneumatic energy storage system configured to utilize solar, wind, sea waves and tidal energy for providing and storing pressurized DSW, according to an embodiment of the present invention; and

Fig. 10 is a schematic cross-sectional view of the hydro-pneumatic energy storage system configured to utilize renewable energy of natural sources, according to another embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

The principles and operation of the hydro-pneumatic energy storage system according to the present invention may be better understood with reference to the drawings and the accompanying description. It should be understood that these drawings are given for illustrative purposes only and are not meant to be limiting. It should be noted that the figures illustrating various examples of the system of the present invention are not to scale, and are not in proportion, for purposes of clarity. It should be noted that the blocks as well other elements in these figures are intended as functional entities only, such that the functional relationships between the entities are shown, rather than any physical connections and/or physical relationships. The same reference numerals and alphabetic characters are utilized for identifying those components which are common in the hydro-pneumatic energy storage system and its components shown in the drawings throughout the present description of the invention. Examples of constructions are provided for selected elements. Those versed in the art should appreciate that many of the examples provided have suitable alternatives which may be utilized.

Referring to **Fig. 1**, a schematic cross-sectional view of a hydro-pneumatic energy storage system **10** is illustrated, according to one embodiment of the present invention. The hydro-pneumatic energy storage system **10** includes a floating support structure **11** and a sea-bottom mounted structure **12**.

According to some embodiments, the floating support structure **11** includes a floating support platform **14** and a floating air chamber **111** having a volume for holding compressed air, and mounted on the floating support platform **14**. The volume of the air chamber **111** has a sufficient value to provide necessary buoyant force to the floating support platform **14**.

It should be understood that the floating structure of the floating support platform structure **11** may also provide support for ancillary systems and services pertaining to, but not limited to, offshore wind farm operation/maintenance systems (not shown), oil and gas infrastructures (not shown), a floating artificial island (not shown) that can utilize the hydro-pneumatic energy storage system **10** for generation of electricity for a grid, providing cooling for buildings and technical systems as well as for other services.

According to some embodiments, the sea-bottom mounted structure **12** includes a sea-bottom accumulator chamber **122**, enabling deep sea water to be stored under pressure of the compressed air located in the sea-bottom accumulator chamber **122**.The sea-bottom mounted structure **12** also includes a sea water inlet pipeline **123** passing from a DSW region to the sea-bottom accumulator chamber **122**. The sea water inlet pipeline **123** is hydraulically coupled to an inlet port **135** of the sea-bottom accumulator chamber **122**. When desired, the inlet end **124** of the sea water inlet pipeline **123** may extend further offshore than the floating support structure **11** to source colder DSW from deeper waters.

The floating air chamber **111** is interconnected to the sea-bottom accumulator chamber **122** through an air umbilical **15**. The air umbilical **15** includes an air conduit that provides a pneumatic communication enabling for linking the compressed air volumes of the floating air chamber **111** and the sea-bottom accumulator chamber **122**. The air umbilical **15** enables effectively increasing the compressed air volume of the sea-bottom accumulator chamber **122**, thereby improving the pressure transient response characteristics of the energy storage system under the influence of an intermittent intake of DSW supplied by a prime mover into the sea-bottom accumulator chamber **122**.

The floating support structure **11** can be maintained in a stable position via a set of mooring lines **112** configured for anchoring the floating support structure **11**. According to the embodiment shown in **Fig. 1**, the floating support structure **11** is anchored to the sea-bottom mounted structure **12**. According to another embodiment, the floating support structure **11** can be anchored directly to the sea-bed **15**.

According to the embodiment shown in **Fig. 1**, the sea-bottom mounted structure **12** is rigidly fixed to the sea-bed **15** through structural elements including a set of driven piles **121** that can be inserted in the sea-bed **15**. According to another embodiment, the sea-bottom mounted structure **12** can be rigidly fixed to the sea-bed **15** through a gravity-based system (not shown) including ballasts resting on the sea-bed or anchors depending on the type sea-bed and the depth of the installation site.

As shown in **Fig. 1**, the floating support structure **11**of hydro-pneumatic energy storage system **10** includes one floating air chamber **111** mounted on the floating support platform **14**. It should be understood that when desired a plurality of the floating compressed air chambers **111** can be used to achieve the increase in compressed air volume, which can be simultaneously used for buoyancy and stability. This additional volume can absorb the pressure transients resulting from changes in the state-of-charge of the sea-bottom accumulator chamber **122**.

The air-hydraulic pressure within the floating air chamber **111** communicating with the sea-bottom accumulator chamber **122** should be sufficient to provide sea water to various hydraulic electricity generators and cooling systems. For example, the air-hydraulic pressure within floating air chamber **111** can be in the range of about 150 bar to 160 bar.

It should be understood that generally, floating air chamber **111** and the sea-bottom accumulator chamber **122** can have any desired shape and be constructed of a suitable metal, plastic or composite material with thickness of the walls appropriate to withstand the strain on the walls caused by the air-hydraulic pressure inside the floating air chamber **111** and the sea-bottom accumulator chamber **122**.

According to an embodiment, the floating support structure **11** includes a pneumatic control valve **113** installed in a manifold **114** pneumatically connected to the floating air chamber **111** and configured to enable the hydro-pneumatic energy storage system to be pressurized with compressed air. The floating air chamber **111** of the hydro-pneumatic storage system **10** can be pre-charged with air using one or more air compressors (not shown) that can be either a part of the system or located on a removable infrastructure, such as a barge (not shown). The pneumatic control valve **113** can, for example, be located in an unwetted area of the floating support platform **14** where it is easily accessible. When required, the system **10** can also include one or several safety valves (not shown) that can automatically open when pressure in the floating air chamber **111** reaches a dangerous level.

According to an embodiment, the sea-bottom mounted structure **12** includes an outlet pipeline **125** coupled to an outlet **127** of the sea-bottom accumulator chamber **122**. The outlet pipeline **125** is equipped with an outlet hydraulic control valve **126** arranged in the outlet pipeline **125**. The hydraulic control valve **126** is configured to regulate the DSW flow from the system such that a desired flow rate of egress of the DSW is maintained over specified periods of time through the outlet pipeline **125**.

In operation, the deep sea water transferred through the outlet pipeline **125** can be supplied to a hydraulic turbine (not shown) coupled to an electrical generator for generating electricity. After passing the hydraulic turbine, the deep sea water may still be used for cooling purposes as long as the exit pressure is high enough to allow the flow of the deep sea water across the pipeline up to the point where such cooling is required.

According to some embodiments, the hydro-pneumatic energy storage system **10** includes a control system generally indicated by a reference numeral **17**. The control system **17** is coupled, *inter alia*, to the pneumatic control valve **113** and to the outlet hydraulic control valve **126**.

The control system **17** is a computer system distributed throughout the floating support platform **14** and the sea-bottom mounted structure **12**. Generally, the control system **17** may include, without limitations, flow meters, sensors, actuators, monitoring devices, as well as other similar or suitable devices. Each may be a commercially available component. The control system **17** also includes an electronic controller **170** programmed with a software model stored in a computer-readable medium (not shown), and configured for controlling operation of the hydro-pneumatic energy storage system **10**.

In the exemplary embodiment shown in **Fig. 1**, the electronic controller **170** of the control system is installed at the floating support platform **14**. However, when desired, the electronic controller of the control system can be installed at the sea-bed mounted structure **12**. Likewise, the electronic controller of the control system can be arranged at some intermediate position in the system.

For measuring pressure of the air within the floating air chamber **111** and within the volume of the sea-bottom accumulator chamber **122** that is unoccupied by DSW, the control system includes one or more pneumatic pressure sensors (not shown) that can be operable for producing air pressure sensor signals throughout operation of the system. Likewise, the control system includes one or more hydraulic pressure sensors (not shown) that can be operable for producing hydraulic pressure sensor signals throughout operation of the system. The location of the pneumatic and hydraulic pressure sensors depends on the specific configuration of the system. For example, the pneumatic pressure sensors can be arranged in the floating air chamber **111** and/or in the sea-bottom accumulator chamber **122**. In turn, the hydraulic pressure sensors can be arranged within the sea water inlet pipeline **123** to measure a pressure of the ingress flow and within the outlet pipeline **125** to measure a pressure of the egress flow. When required, the control system **17** can alert the operator of any detrimental pressure drops. The gas and hydraulic pressure sensor signals can be relayed to the electronic controller **170** via a connecting wire, or wirelessly.

According to some embodiments, the control system **17** includes an upper water level sensor **128** and a lower level sensor **129** arranged inside the sea-bottom accumulator chamber **122** of the sea bottom mounted structure **12**. The upper water level sensor **128** and the lower level sensor **129** are configured for producing minimal and maximal DSW level signals, correspondingly, to ensure that the level of DSW inside the sea-bottom accumulator chamber **122** is within a predetermined level limit range.

To provide regulation of the flow rate, the control system **17** of the hydro-pneumatic energy storage system **10** can include one or more flow meters arranged within the sea water inlet pipeline **123** and within the outlet pipeline **125**, and configured for producing DSW flow sensor signals representative of the DSW ingress flow within the sea water inlet pipeline and the DSW egress flow within the outlet pipeline **125**, correspondingly.

The electronic controller **170** is operatively coupled to the pneumatic pressure sensors, the hydraulic pressure sensor, water level sensors and to the flow meters for controllable pumping DSW to the sea-bottom accumulator chamber **122** and for controllable discharge of the DSW from the sea-bottom accumulator chamber **122**. The electronic controller **170** is, *inter alia*, responsive to the air pressure sensor signals, the hydraulic pressure sensor signals, the minimal and maximal DSW level signals and the DSW flow sensor signals, respectively. The electronic controller **170** is capable of generating control signals to control operation of the pneumatic control valve **113** and the outlet hydraulic control valve **126**. The location of flow meters along the sea water inlet pipeline **123** and within the outlet pipeline **125** depends on the specific system configuration.

In particular, when the DSW level becomes lower than the lower level limit, the electronic controller **170** generates a control signal to close the hydraulic control valve **126**. This enables avoiding compressed air from being lost and having the system de-pressurized. Likewise, when the DSW level exceeds an upper level limit, the electronic controller **170** generates control signals to open the hydraulic control valve **126**, so as to decrease the level to a desired value.

The discharge flow of the DSW within the outlet pipeline **125** can be measured by an outlet flow meter **163** that is operable for producing a DSW outlet flow sensor signal. The flow meter **163** is coupled to the electronic controller **17** of the control system which is, *inter alia*, responsive to the DSW outlet flow sensor signal and capable of generating a valve control signal for controlling the operation of the hydraulic control valve **126**. Depending on the power attributes of the hydro-pneumatic energy storage system **10** (input availability and output demand), a desired egress flow rate from the system can be specified and maintained by the electronic controller **170** during operation of the system, while the line hydraulic pressure is maintained by the gas pressure in the floating air chamber **111** and/or in the sea-bottom accumulator chamber **122**. The outlet hydraulic control valve **126** ensures a stable supply of pressurized DSW to produce constant electrical power output over stipulated periods, hence overcoming certain technical problems encountered with conventional technology when feeding electricity to the grid.

According to some embodiments, hydro-pneumatic energy storage system **10** includes a compression system schematically indicated by a reference numeral **13**. The compression system **13** includes a prime mover (not shown) and a pump **132** engaged with the prime mover, and configured for pumping deep sea water (DSW) into the sea-bottom accumulator chamber **122**. In the sea-bottom accumulator chamber **122**, the DSW is pressurized**,** thereby also compressing the air. The pressurized DSW is stored at high pressure in the hydro-pneumatic energy storage system **10**. The compression system **13** is hydraulically coupled to an inlet port **135** of the sea-bottom accumulator chamber **122** through the sea water inlet pipeline **123**. Various implementations of the compression system **13** will be described hereinbelow.

According to some embodiments, the electronic controller **170** is also operatively coupled to the pump **132** for controllable pumping DSW into the sea-bottom accumulator chamber **122**. In particular, when the DSW level becomes lower than the lower level limit, in response to the minimal DSW level signal of the lower level sensor **129**, the electronic controller **170** generates a control signal to close the hydraulic control valve **126** and/or turn-on the pump **132** to start pumping deep sea water into the the sea-bottom accumulator chamber **122**. On the other hand, when the DSW level in the sea-bottom accumulator chamber **122** exceeds an upper level limit, in response to the maximal DSW level signal of the upper level sensor **128**, the electronic controller **170** generates a control signal to open the hydraulic control valve **126** and/or turn-off the pump **132** to stop pumping deep sea water into the sea-bottom accumulator chamber **122**, so as to decrease the level to a desired value.

The compressed air within the floating air chamber **111** and within the volume of the sea-bottom accumulator chamber **122** serves the role of a pneumatic accumulator in damping fluctuations in pressure arising from the intermittent supply of DSW from the prime mover and transients induced by the operation of the outlet hydraulic control valve **126**. The energy storage capability of the proposed system depends on the pressure and volume of the DSW contained in the sea-bottom accumulator chamber **122**. While the volume is fixed depending on the design of the adopted structure, the pressure may be varied depending on the operational requirements of the system. It should be noted that according to the proposed invention, any loss of pneumatic pressure would not cause the hydro-pneumatic energy storage system **10** to become structurally unstable.

Referring to **Fig. 2**, a schematic cross-sectional view of a hydro-pneumatic energy storage assembly **20** is illustrated, according to an embodiment of the present invention. According to this embodiment, a hydro-pneumatic energy storage assembly includes a plurality of the hydro-pneumatic energy storage systems (**10** shown in **Fig. 1**) which are arranged in series and are interconnected through sea water pipelines. Such a configuration provides enhanced buoyancy and stability to the storage system.

As shown in **Fig. 2**, DSW is provided by the compression system **13** to the sea-bottom accumulator chamber **122** of the first hydro-pneumatic energy storage system **10a** through the sea water inlet pipeline **123**. An outlet pipeline **145** of the sea-bottom mounted structure of first hydro-pneumatic energy storage system **10a** is coupled to an inlet port **135** of the sea-bottom accumulator chamber **122** of the second hydro-pneumatic energy storage system **10b** and so on. The floating air chambers **111** of the storage systems **10a**, **10b**, etc. are coupled by pneumatic pipelines **155**.

In this case, the outlet pipeline of the storage system **10a** operates as a sea water inlet pipeline of the second storage system **10b**. The deep sea water exiting the last (in series) hydro-pneumatic energy storage system can be supplied to a hydraulic turbine (not shown) coupled to an electrical generator (not shown) for generating electricity. After passing the hydraulic turbine, the deep sea water may still be used for cooling purposes as long as the exit pressure is high enough to allow the flow of the deep sea water across the pipeline up to the point where such cooling is required.

Referring to **Fig. 3**, a schematic cross-sectional view of a hydro-pneumatic energy storage assembly **30** is illustrated, according to another embodiment of the present invention. This embodiment is suitable in cases where anchoring points are to be located considerably away from the prime mover mounted on the floating support structures **11**. This configuration may be installed in a way to serve the dual purpose of acting as anchoring locations and also as energy storage.

As shown in **Fig. 3**, the hydro-pneumatic energy storage assembly **30** includes a plurality of the floating support structures **11** interconnected with a plurality of the sea-bottom mounted structures **12** through deep sea water pipelines **145** and through pneumatic pipelines **155**. Specifically, the sea-bottom mounted structures **12** of the assembly **30**are arranged in series and are interconnected through sea water pipelines **145** similar to assembly (**20** in **Fig. 2**). The deep sea water exiting the last (in series) sea-bottom mounted structures **12** of the assembly **30** can be supplied to an electric hydraulic turbine for generating electricity and also used for cooling purposes.

The hydro-pneumatic energy storage assembly **30** differs from the assembly (**20** in **Fig. 2**) in the fact that the floating air chamber **111** of each floating support structure **11** is interconnected with the sea-bottom accumulator chambers **122** of two neighboring sea-bottom mounted structures **12** through pneumatic pipelines **155,** however other interconnecting configurations are also contemplated. According to the embodiment shown in **Fig. 3**, all the floating compressed air chambers **111** and the sea-bottom accumulator chambers **122** communicate, thereby forming a common air volume composed from air volumes of the floating compressed air chambers **111** and the air volumes of the sea-bottom accumulator chambers **122**. This combined volume can facilitate smoothing of the pressure transients resulting from changes in the state-of-charge of the last sea-bottom accumulator chamber **122**.

The floating support assemblies **11** can be maintained in a stable position via a set of mooring lines **112** configured for anchoring the floating support structure **11**. According to the embodiment shown in **Fig. 3**, the floating support structures **11** are anchored to the sea-bottom mounted structures **12**. According to some embodiments, catenary moorings are used as anchor lines for anchoring the floating support structures **11**.

Turning now to **Figs. 4** through **8**, various types of the compression system **13** suitable for providing deep sea water (DSW) to the hydro-pneumatic energy storage system **10** for storing the DSW at high pressure are described hereinbelow. It should be noted that not all components of the hydro-pneumatic energy storage system **10** are shown and/or indicated in these figures, but mainly those which are necessary for description of operation of the compression system **13**.

Fig. 4 is a schematic cross-sectional view of the hydro-pneumatic energy storage system **10** connected to an electricity grid network, according to an embodiment of the present invention.

This embodiment allows for the integration of the energy storage system **10** into an offshore electrical power grid. According to this embodiment, the pump **132** of the compression system **13** is an electric pump that is coupled to an offshore electrical power grid **41** and powered by electricity. In operation, the pump **132** pumps deep sea water and supplies it to the sea-bottom accumulator chambers **122** where the DSW is stored at high pressure. This embodiment enables excess electrical energy in the offshore electrical power grid to be converted to hydro-energy, and be stored in the system through air compression.

The hydro-energy may be converted back to electricity and fed into the grid. Thus, DSW exiting the hydro-pneumatic energy storage system can be controllably supplied at a desired pressure to a hydro-electric power unit **42**. The hydro-electric power unit **42** includes a hydraulic turbine (not shown) coupled to an electrical generator (not shown). When desired. the deep sea water exiting the hydroelectric power unit **42** may still be used for cooling purposes as long as the exit pressure is high enough to allow the flow of the deep sea water across the pipeline up to the point where such cooling is required.

The hydro-pneumatic energy storage system **10**can be integrated with offshore floating electrical wind turbines. **Fig. 5** is a schematic cross-sectional view of the hydro-pneumatic energy storage system **10** configured to utilize wind energy for providing and storing pressurized DSW, according to an embodiment of the present invention.

According to this embodiment, the compression system **13** of the hydro-pneumatic energy storage system **10** is mounted on the floating support platform **14** of the floating support structure **11**. As described above, the compression system **13** includes the pump **132** engaged with the prime mover **130**, and configured for pumping and pressurizing sea water in order to store it at high pressure.

According to this embodiment, the prime mover **130** of the compression system **13** includes an electrical wind turbine system **51** arranged on a tower **134** that is mounted on the floating support platform **14**, however other arrangements of the electrical wind turbine system **51** are also contemplated. In this case the upper floating support structure **11** serves a dual role: (i) to provide the necessary upthrust to support the floating electrical wind turbine system **51** and (ii) to serve as a platform for holding the air chamber **111**.

The electrical wind turbine system **51** has a plurality of wind vanes **133** disposed to intercept prevailing winds, a rotor **135** driven by the wind and an electrical generator **52**. The electrical generator **52** can, for example, be arranged in a nacelle **136** of the turbine system **131** and connected to an offshore electrical power grid **53**. The rotor **135** of the electrical wind turbine system **51** is operatively engaged with the electrical generator **52** to generate output electrical power and provide it to the grid.

The floating electrical wind turbine system **51** generates electricity and is therefore electrically interfaced with the storage system and the grid. Similar to the embodiment shown in **Fig. 4,** the pump **132** of the compression system **13** is coupled to the offshore electrical power grid **53**. In operation, the pump **132** is powered by the grid**,** pumps deep sea water and supplies it to the sea-bottom accumulator chambers **122** where the DSW is stored at high pressure.

DSW exiting the hydro-pneumatic energy storage system can be controllably supplied at a desired pressure to the hydro-electric power unit **42**. The deep sea water exiting the hydroelectric power unit **42** may still be used for cooling purposes as long as the exit pressure is high enough to allow the flow of the deep sea water across the pipeline up to the point where such cooling is required.

Fig. 6 is a schematic cross-sectional view of the hydro-pneumatic energy storage system **10** configured to utilize wind energy for providing and storing pressurized DSW, according to another embodiment of the present invention. According to this embodiment, the compression system **13** of the hydro-pneumatic energy storage system **10** includes the pump **132** that is also mounted on the floating support platform **14** of the floating support structure **11**.

In this case, the prime mover **130** associated with the compression system **13** includes a hydraulic wind turbine system **61**. The hydraulic wind turbine system **61** can, for example, be arranged on the tower **134** that is mounted on the floating support platform **14**, however other arrangements of the hydraulic wind turbine system **61** are also contemplated. For instance, the hydraulic wind turbine system can be mounted on a mast (not shown) fixed to the sea-bed.

Contrary to the embodiment shown in **Fig. 5**, in the case shown in **Fig. 6**, the electrical generator (**52** in **Fig. 5**) is replaced by a pump that supplies pressurized sea water to the hydro-pneumatic energy storage system **10**. The hydraulic wind turbine system **61** has a plurality of wind vanes **133** disposed to intercept prevailing winds and a rotor **135** driven by the wind. According to this embodiment, the rotor **135** of the hydraulic wind turbine system **61** is operatively engaged with the pump **132** that is arranged in a nacelle **136** of the wind turbine system **61**. An example of the pump **132** includes, but is not limited to, a positive displacement hydraulic pump. The rotor **135** can, for example, be directly connected to the hydraulic pump **132**.

In operation, deep sea water (DSW) flows up and down the turbine tower by means of the hydraulic pump **132**. The pump **132** can, for example, be a pressure boost pump to enable the water to go up the tower. The pump **132** is operatively engaged to draw DSW through the sea water pipeline **123** to supply the DSW to the sea-bottom accumulator chamber **122**, where the DSW is stored at high pressure.

DSW exiting the hydro-pneumatic energy storage system can be controllably supplied at a desired pressure through the outlet pipeline **125** to the hydro-electric power unit **42**. The deep sea water exiting the hydroelectric power unit **42** may pass through a heat exchanger **62** in order to be used for cooling purposes as long as the exit pressure is high enough to allow the flow of the deep sea water across the pipeline up to the point where such cooling is required.

The hydro-pneumatic energy storage system **10** can be integrated with offshore floating electrical turbines utilizing tidal energy. **Fig. 7** is a schematic cross-sectional view of the hydro-pneumatic energy storage system **10** configured to utilize tidal energy for providing and storing pressurized DSW, according to an embodiment of the present invention.

According to this embodiment, the compression system **13** of the hydro-pneumatic energy storage system **10** is mounted on the floating support platform **14** of the floating support structure **11**. As described above, the compression system **13** includes the pump **132** that is engaged with the prime mover **130** and configured for pumping and pressurizing sea water in order to store it at high pressure.

According to this embodiment, the prime mover **130** includes an electrical tidal turbine system **71** that is mounted on the floating support platform **14**, however other arrangements of the electrical tidal turbine system **71** are also contemplated. In this case the upper floating support structure **11** serves a dual role: (i) to provide the necessary upthrust to support the floating electrical tidal turbine system **71** and (ii) to serve as a platform for holding the air chamber **111**.

The electrical tidal turbine system **71** has a plurality of vanes **72** disposed to intercept prevailing tidal current, a rotor **73** driven by the tidal current and an electrical generator **74**. The rotor of the electrical tidal turbine system **71** is operatively engaged with the electrical generator **74** to generate output electrical power. When desired, the electrical generator **74** can be connected to an offshore electrical power grid **75**.

The floating electrical tidal turbine system **71** generates electricity, and is therefore electrically interfaced with the storage system **10** and the grid **75**. Similar to the embodiment shown in **Figs. 4** and **5,** the pump **132** of the compression system **13** is an electrical pump that is coupled to the offshore electrical power grid **75**. In operation, the pump **132** that is powered by the grid, pumps deep sea water and supplies it to the sea-bottom accumulator chambers **122** where the DSW is stored at high pressure.

Fig. 8 is a schematic cross-sectional view of the hydro-pneumatic energy storage system **10** configured to utilize sea tidal energy for providing and storing pressurized DSW, according to another embodiment of the present invention. According to this embodiment, the pump **132** of the compression system **13** is also mounted on the floating support platform **14** of the floating support structure **11**.

In this case, the prime mover **130** engaged with the compression system **13** includes a hydraulic tidal turbine system **81** that is mounted on the floating support platform **14**, however other arrangements of the hydraulic tidal turbine system **81** are also contemplated. Contrary to the embodiment shown in **Fig. 7**, in the case shown in **Fig. 8**, the electrical generator (**73** in **Fig. 7**) is replaced by a hydraulic pump that supplies pressurized sea water to the hydro-pneumatic energy storage system **10**.

The hydraulic tidal turbine system **81** has a plurality of vanes **82** disposed to intercept prevailing tidal current and a rotor **83** driven by the tidal current. According to this embodiment, the rotor **83** of the hydraulic wind turbine system **81** is operatively engaged with the pump **132**. According to this embodiment, the pump **132** can, for example, be a positive displacement hydraulic pump. The rotor **135** can, for example, be directly connected to the hydraulic pump **132**. In operation, the pump **132** is operatively engaged with the prime mover to draw DSW through the sea water pipeline **123** and to supply the DSW to the sea-bottom accumulator chamber **122**, where the DSW is stored at high pressure.

DSW exiting the hydro-pneumatic energy storage system can be controllably supplied at a desired pressure through the outlet pipeline **125** to the hydro-electric power unit **42**. The deep sea water exiting the hydroelectric power unit **42** may pass through the heat exchanger **62** in order to be used for cooling purposes as long as the exit pressure is high enough to allow the flow of the deep sea water across the pipeline up to the point where such cooling is required.

It should be understood that, when desired, multiple renewable energy systems can be electrically interfaced with the hydro-pneumatic energy storage system **10**. **Fig. 9** is a schematic cross-sectional view of the hydro-pneumatic energy storage system **10** configured to utilize solar, wind, sea waves and tidal energy for providing and storing pressurized DSW, according to an embodiment of the present invention.

As described above, the compression system (**13** in **Fig. 1**) of the hydro-pneumatic energy storage system **10** includes the pump **132** engaged with the prime mover **130**, and configured for pumping and pressurizing sea water in order to store it at high pressure. According to this embodiment, the prime mover that is engaged with the compression system **13**, includes a plurality of electrical energy systems utilizing natural energy sources generating output electrical power.

According to this embodiment, the prime mover includes an electrical wind turbine system **91**, an electrical tidal turbine system **92**, an electrical sea wave energy convertor system **93** and an electrical solar system **94**. All these electrical systems are coupled to an offshore electrical power grid **95** to provide output electrical power generated from natural energy sources.

As shown in **Fig. 9**, the electrical solar system **94** is mounted on the floating support platform **14**, while the electrical wind turbine system **91**, the electrical tidal turbine system **92** and the electrical sea wave energy convertor system **93** are mounted on the sea bottom, however other configurations of the prime mover **130** are also contemplated. For example, as shown in **Figs. 5** and **7**, the electrical wind turbine system **91** and the electrical tidal turbine system **92** can also be mounted on the floating support platform **14**. Likewise, when desired, the electrical solar system **94** can be mounted on a mast (not shown) that is fixed to the sea bottom. Although only one of the electrical energy systems for each type of natural energy sources is shown in **Fig. 9**, it should be understood that any desired number of the electrical energy systems can be interfaced with the storage system **10** and the grid **95**.

Similar to the embodiments shown in **Figs. 4, 5** and **7**, the pump **132** of the compression system **13** is coupled to the offshore electrical power grid **95**. In operation, the pump **132** is powered by the grid, pumps deep sea water and supplies it to the sea-bottom accumulator chambers **122** where the DSW is stored at high pressure.

Referring to **Fig. 10**, a schematic cross-sectional view of the hydro-pneumatic energy storage system **10** configured to utilize renewable energy of natural sources is illustrated, according to another embodiment of the present invention. According to this embodiment, multiple renewable energy systems can be associated with the hydro-pneumatic energy storage system **10** by using a hydraulic network **150**.

According to this embodiment, the prime mover **130** includes a hydraulic wind turbine system **101**, a hydraulic sea wave energy convertor system **102** and a hydraulic tidal turbine system **103**. As shown in **Fig. 10**, the hydraulic wind turbine system **101** is mounted on the floating support platform **14**, while the hydraulic sea wave energy convertor system **102** and the hydraulic tidal turbine system **103** are mounted on the sea bottom **104**, however other configurations of the prime mover **130** are also contemplated. For example, as shown in **Fig. 8**, the hydraulic tidal turbine system **92** can also be mounted on the floating support platform **14**.

According to this embodiment, the compression system **13** includes a hydraulic pump **132a** associated with the hydraulic wind turbine system **101**, a hydraulic pump **132b** associated with the hydraulic sea wave turbine system **102** and a hydraulic pump **132c** associated with the hydraulic tidal turbine system **103** of the prime mover **130**. For example, the pumps **132a**, **132b** and **132** can be positive displacement hydraulic pumps.

In operation, the pumps **132a**, **132b** and **132c** pump deep sea water and draw it through the sea water pipelines**123a**, **123b** and **123c** to supply the DSW to the sea-bottom accumulator chamber **122**, where the DSW is stored at high pressure.

As such, those skilled in the art to which the present invention pertains, can appreciate that while the present invention has been described in terms of preferred embodiments, the concept upon which this disclosure is based may readily be utilized as a basis for the designing of other structures, systems and processes for carrying out the several purposes of the present invention.

Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting.

Finally, it should be noted that the word “comprising” as used throughout the appended claims is to be interpreted to mean “including but not limited to”.

It is important, therefore, that the scope of the invention is not construed as being limited by the illustrative embodiments set forth herein. Other variations are possible within the scope of the present invention as defined in the appended claims. Other combinations and sub-combinations of features, functions, elements and/or properties may be claimed through amendment of the present claims or presentation of new claims in this or a related application. Such amended or new claims, whether they are directed to different combinations or directed to the same combinations, whether different, broader, narrower or equal in scope to the original claims, are also regarded as included within the subject matter of the present description.

CLAIMS:

1. A hydro-pneumatic energy storage system for deep sea water (DSW), comprising:

a floating support structure including a floating support platform, and a floating air chamber mounted on the floating support platform and configured for holding compressed air;

a sea-bottom mounted structure including a sea-bottom accumulator chamber configured for holding the compressed air and the DSW to store the DSW under pressure of the compressed air; and

an air umbilical pneumatically interconnecting said floating air chamber with said sea-bottom accumulator chamber.

2. The hydro-pneumatic energy storage system of claim 1, wherein the sea-bottom mounted structure includes:

a sea water inlet pipeline passing from a DSW region to the sea-bottom accumulator chamber and hydraulically coupled to an inlet port of the sea-bottom accumulator chamber; and

an outlet pipeline coupled to the sea-bottom accumulator chamber configured to discharge the DSW egress flow.

3. The hydro-pneumatic energy storage system of claim 1, wherein the air chamber has a volume sufficient for the compressed air in the air chamber to provide necessary buoyant force to the floating support platform.

4. The hydro-pneumatic energy storage system of claim 1, wherein the air umbilical includes an air conduit configured to provide a pneumatic communication for linking the compressed air of the floating air chamber with the compressed air of the sea-bottom accumulator chamber.

5. The hydro-pneumatic energy storage system of claim 1, comprising a set of mooring lines configured for anchoring the floating support structure.

6. The hydro-pneumatic energy storage system of claim 5, wherein the floating support structure is anchored to the sea-bottom mounted structure.

7. The hydro-pneumatic energy storage system of claim 6, wherein the floating support structure is anchored to a sea-bed.

8. The hydro-pneumatic energy storage system of claim 1, wherein the sea-bottom mounted structure is rigidly fixed to a sea-bed by driven piles inserted in the sea-bed.

9. The hydro-pneumatic energy storage system of claim 1, wherein the sea-bottom mounted structure is rigidly fixed to the sea-bed through a gravity-based system.

10. The hydro-pneumatic energy storage system of claim 1, wherein the floating support structure includes a pneumatic control valve pneumatically connected to the floating air chamber, and configured to pressurize the hydro-pneumatic energy storage system with compressed air.

11. The hydro-pneumatic energy storage system of claim 2, wherein the sea-bottom mounted structure includes an outlet hydraulic control valve arranged in the outlet pipeline and configured to regulate the DSW egress flow from the sea-bottom accumulator chamber.

12. The hydro-pneumatic energy storage system of claim 11, comprising a control system coupled to the pneumatic control valve and to the hydraulic control valve for controlling operation thereof.

13. The hydro-pneumatic energy storage system of claim 12, wherein the control system comprises at least one device selected from:

at least one pneumatic pressure sensor configured for producing air pressure sensor signals representative of the air pressure in the floating air chamber and/or the sea-bottom accumulator chamber;

at least one hydraulic pressure sensor configured for producing hydraulic pressure sensor signals representative of the DSW pressure within the sea water inlet pipeline and/or within the outlet pipeline;

at least one water level sensor arranged inside the sea bottom mounted structure and configured for producing minimal and maximal DSW level signals when the level of DSW inside the sea-bottom accumulator chamber is out of a predetermined level limit range;

at least one flow meter arranged within the sea water inlet pipeline and within the outlet pipeline, and configured for producing DSW flow sensor signals representative of the DSW flow within the sea water inlet pipeline and within the outlet pipeline; and

an electronic controller operatively coupled to said at least one pneumatic pressure sensor, said at least one hydraulic pressure sensor and said at least one flow meter, and being responsive to said air pressure sensor signals, said hydraulic pressure sensor signals and said DSW flow sensor signals, said electronic controller being capable of generating control signals for controlling the operation of the pneumatic control valve and the hydraulic control valve.

14. The hydro-pneumatic energy storage system of claim 2, comprising a compression system arranged within the sea water inlet pipeline, the compression system including a pump configured for pumping the DSW through the sea water inlet pipeline to the sea-bottom accumulator chamber for storing the DSW at a predetermined pressure.

15. The hydro-pneumatic energy storage system of claim 14, further comprising a prime mover engaged with the compression system and configured to drive the pump.

16. The hydro-pneumatic energy storage system of claim 15, wherein the pump of the compression system is an electric pump that is coupled to an electrical power grid and powered by electricity.

17. The hydro-pneumatic energy storage system of claim 15, wherein the pump of the compression system is a hydraulic pump.

18. The hydro-pneumatic energy storage system of claim 16, wherein the prime mover includes an electrical wind turbine system including:

a rotor driven by wind;

a plurality of wind vanes disposed on the rotor and configured to intercept prevailing winds; and

an electrical generator operatively engaged with the rotor and connected to said electrical power grid, the electrical generator is configured to generate output electrical power and provide it to the grid.

19. The hydro-pneumatic energy storage of claim 16, wherein the prime mover includes an electrical tidal turbine system including:

a rotor driven by tidal current;

a plurality of wind vanes disposed on the rotor and configured to intercept prevailing tidal current; and

an electrical generator operatively engaged with the rotor and connected to said electrical power grid, the electrical generator is configured to generate output electrical power and provide it to the grid.

20. The hydro-pneumatic energy storage system of claim 17, wherein the prime mover includes a hydraulic wind turbine system including:

a rotor driven by wind and mechanically coupled to said hydraulic pump; and

a plurality of wind vanes disposed on the rotor and configured to intercept prevailing winds.

21. The hydro-pneumatic energy storage system of claim 17, wherein the prime mover includes a hydraulic tidal turbine system including:

a rotor driven by tidal current and mechanically coupled to said hydraulic pump for driving thereof; and

a plurality of vanes disposed on the rotor and configured to intercept prevailing tidal current.

22. The hydro-pneumatic energy storage system of claim 15, wherein the pump of the compression system is an electric pump that is coupled to an electrical power grid and powered by electricity; and wherein the prime mover includes at least one renewable energy system configured to generate output electrical power and provide it to the grid and selected from an electrical wind turbine system, an electrical tidal turbine system, an electrical sea wave energy convertor system and an electrical solar system.

23. The hydro-pneumatic energy storage system of claim 15, wherein the pump of the compression system is a hydraulic pump, and wherein the prime mover includes at least one renewable energy system mechanically coupled to said hydraulic pump for driving thereof, said at least one renewable energy system selected from a hydraulic wind turbine system, a hydraulic sea wave energy convertor system and a hydraulic tidal turbine system.

24. A hydro-pneumatic energy storage assembly comprising a plurality of the hydro-pneumatic energy storage systems of claim 1 arranged in series and interconnected through sea water pipelines.

25. A hydro-pneumatic energy storage assembly comprising a plurality of floating support structures interconnected with a plurality of sea-bottom mounted structures through deep sea water pipelines and through pneumatic pipelines, wherein the sea-bottom mounted structures are arranged in series and are interconnected through sea water pipelines, and wherein the floating air chamber of each floating support structure is interconnected with the sea-bottom accumulator chambers of two neighboring sea-bottom mounted structures through pneumatic pipelines.

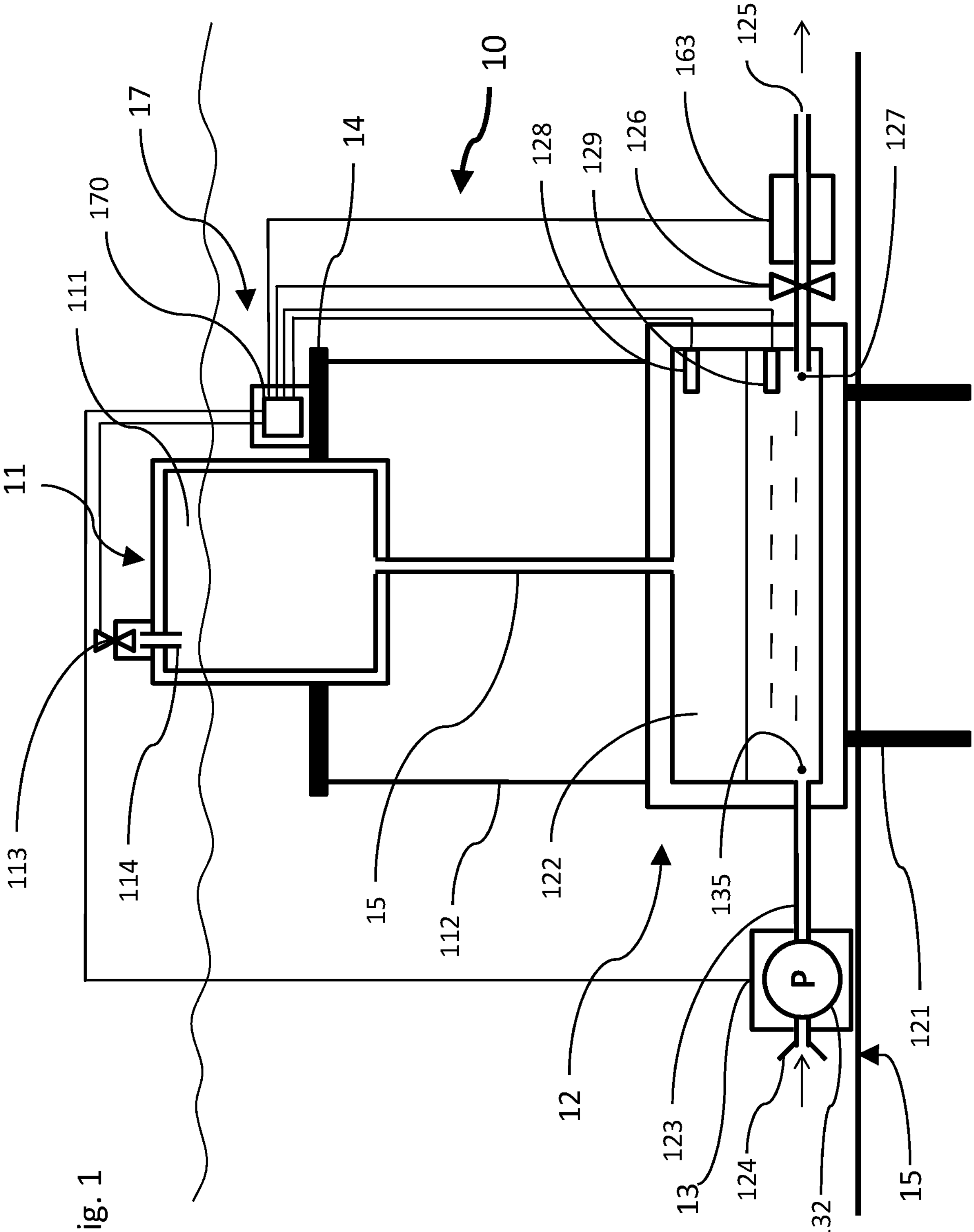
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Fig. 1

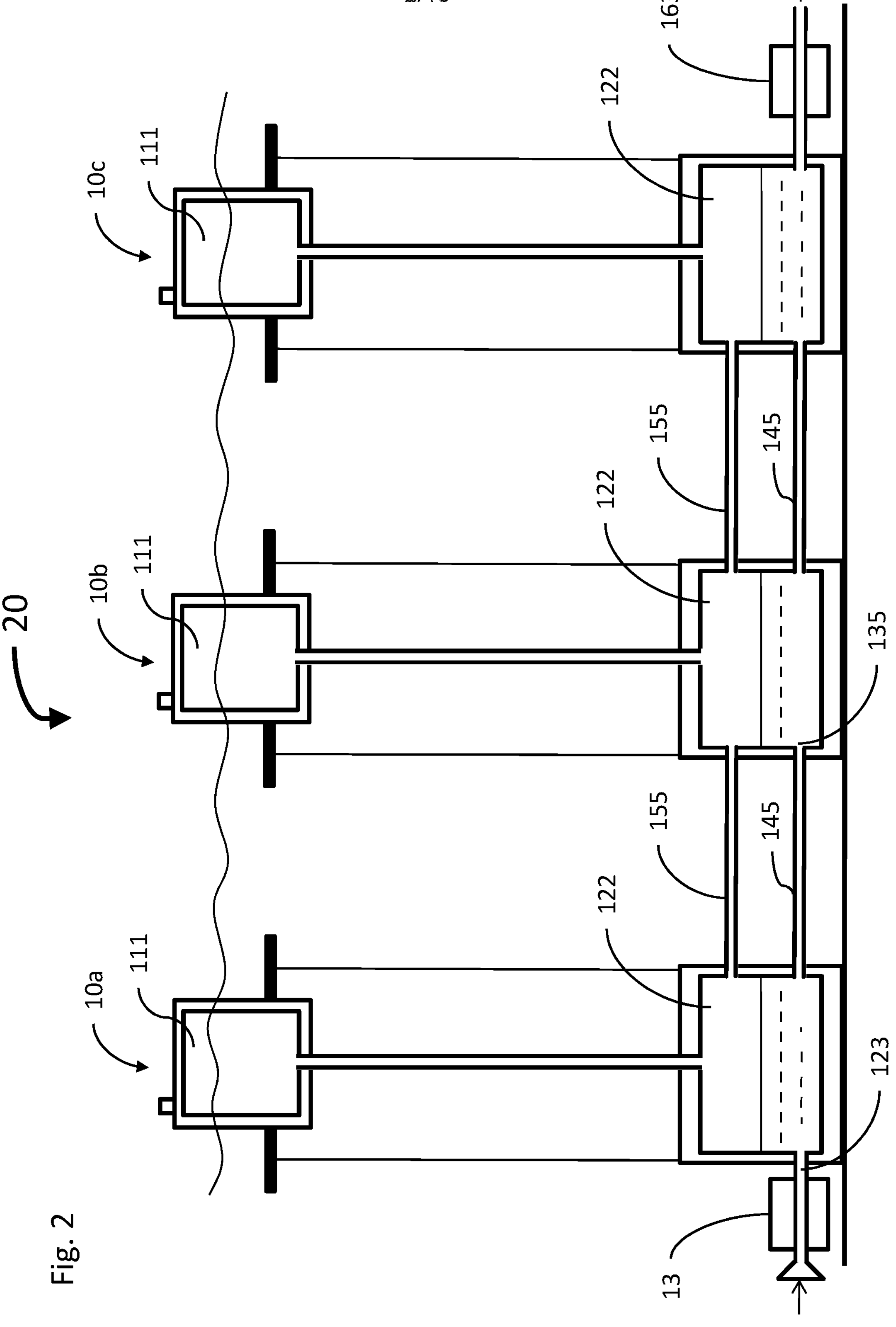
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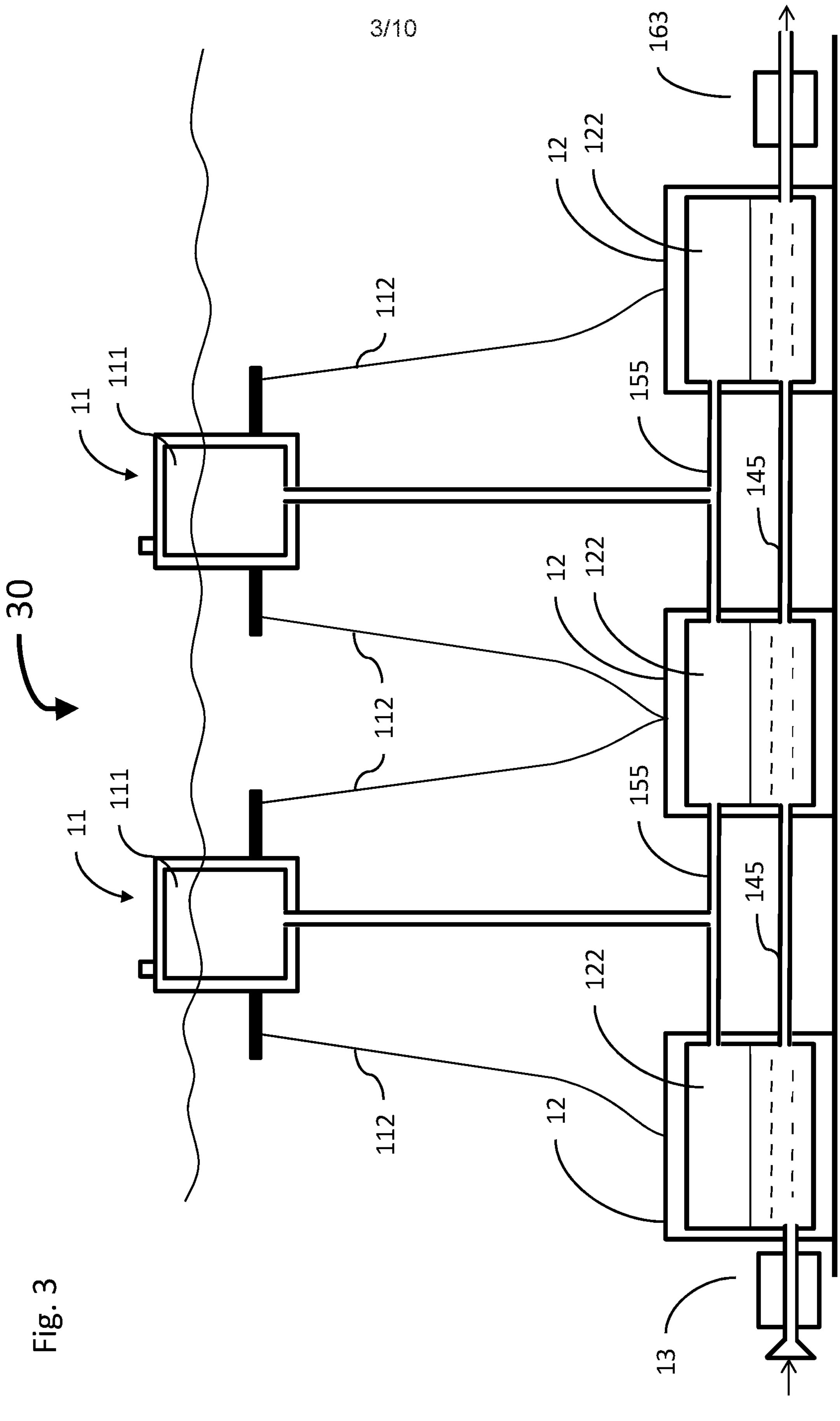
Fig. 2



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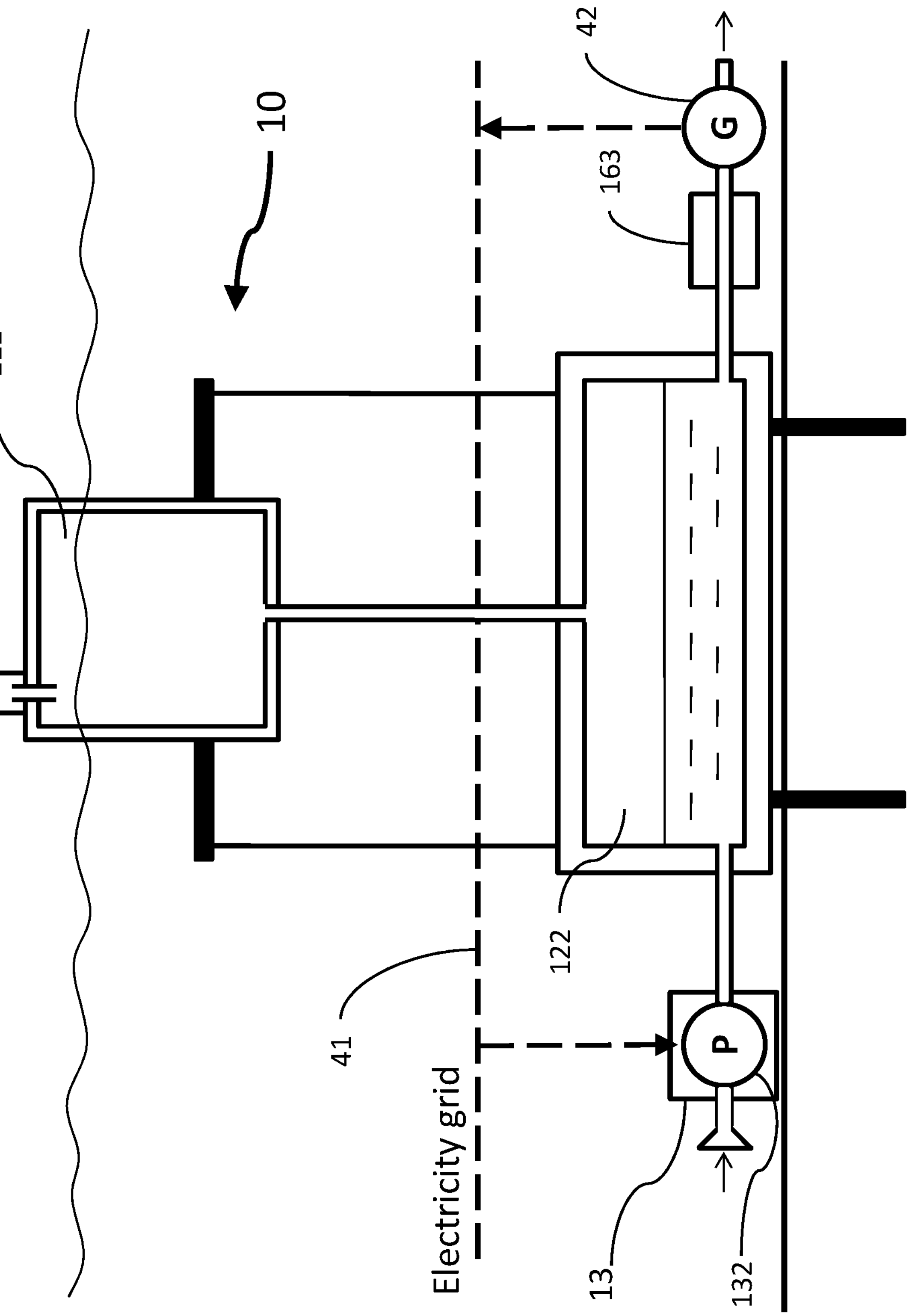

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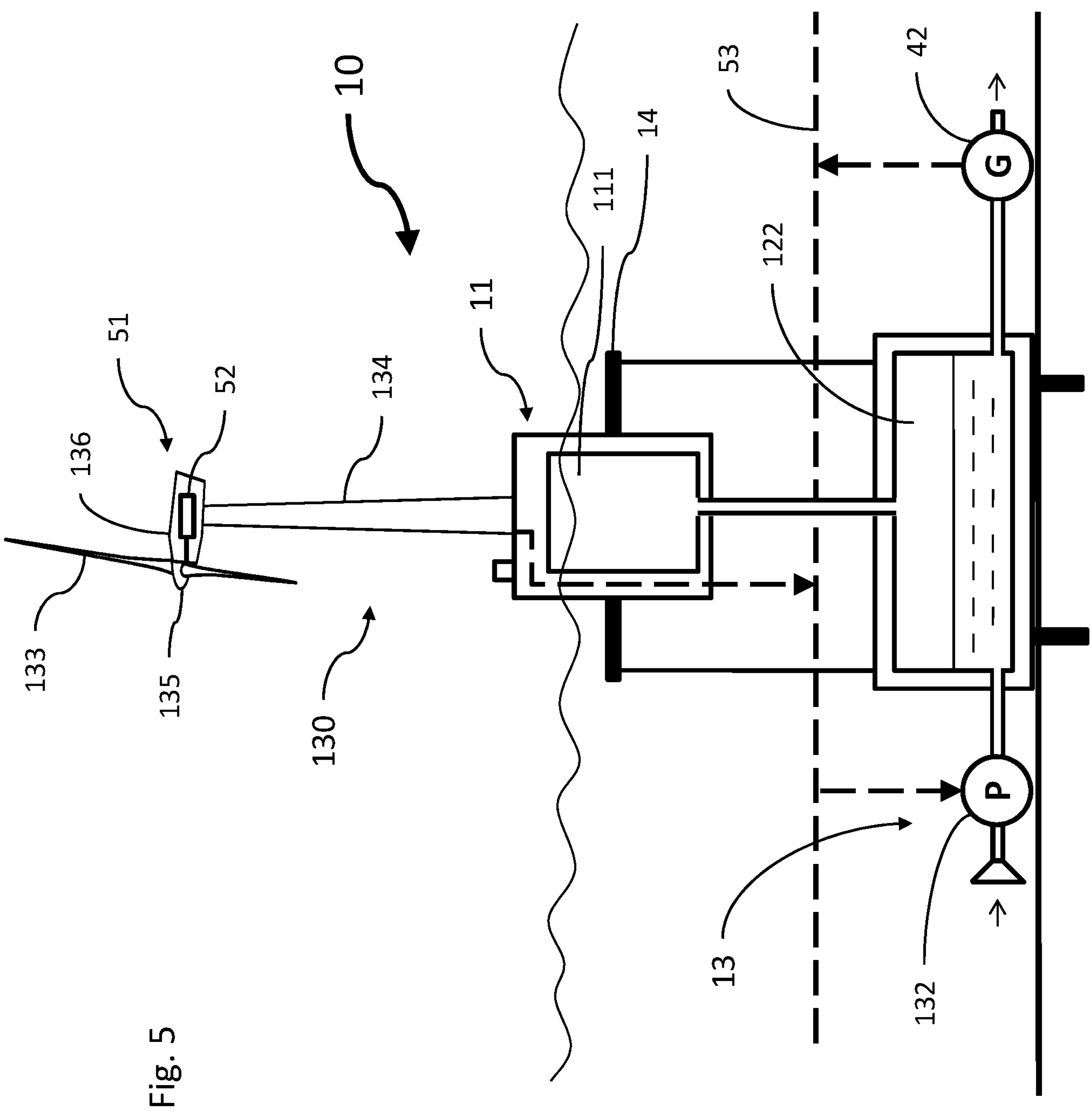

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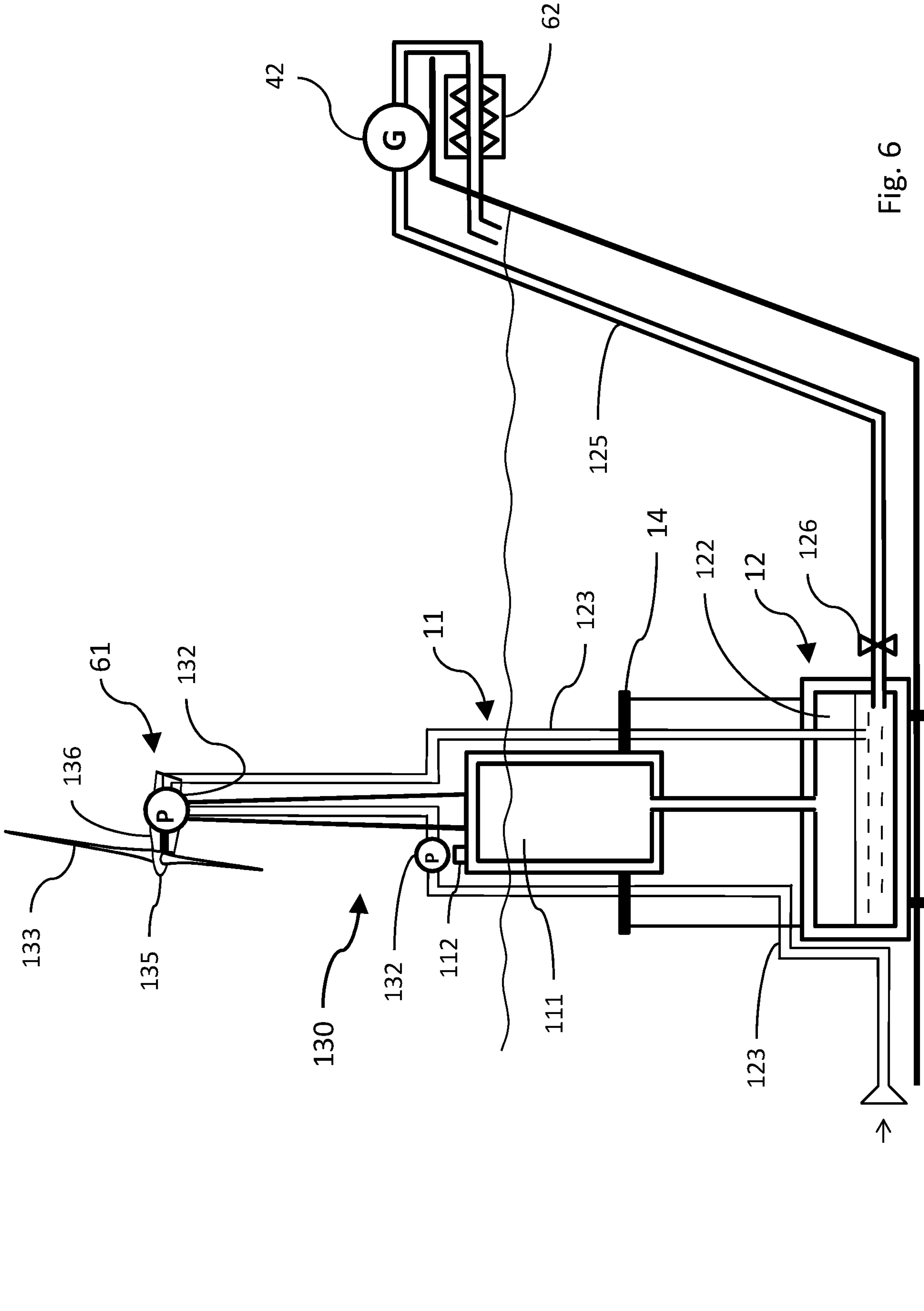
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Fig. 6

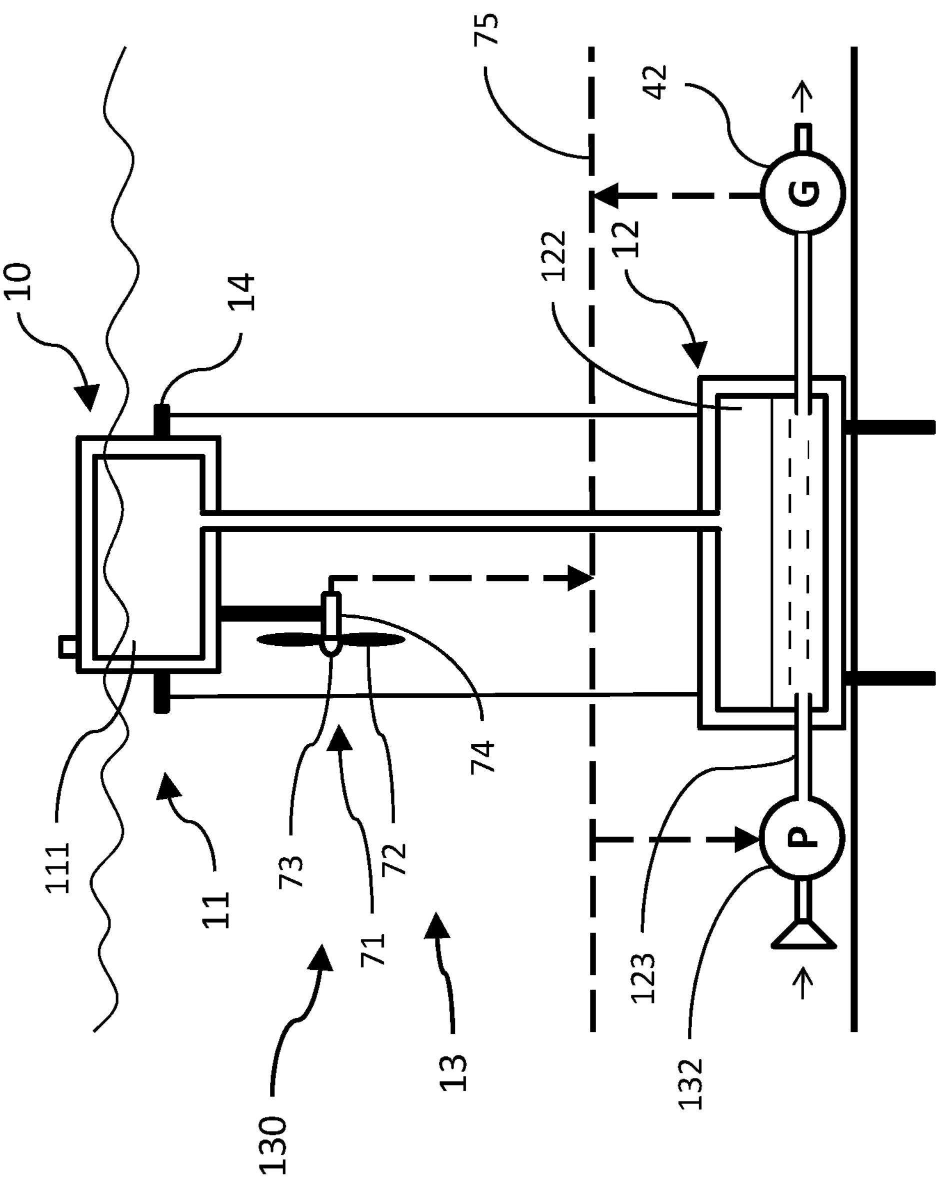


Fig. 7

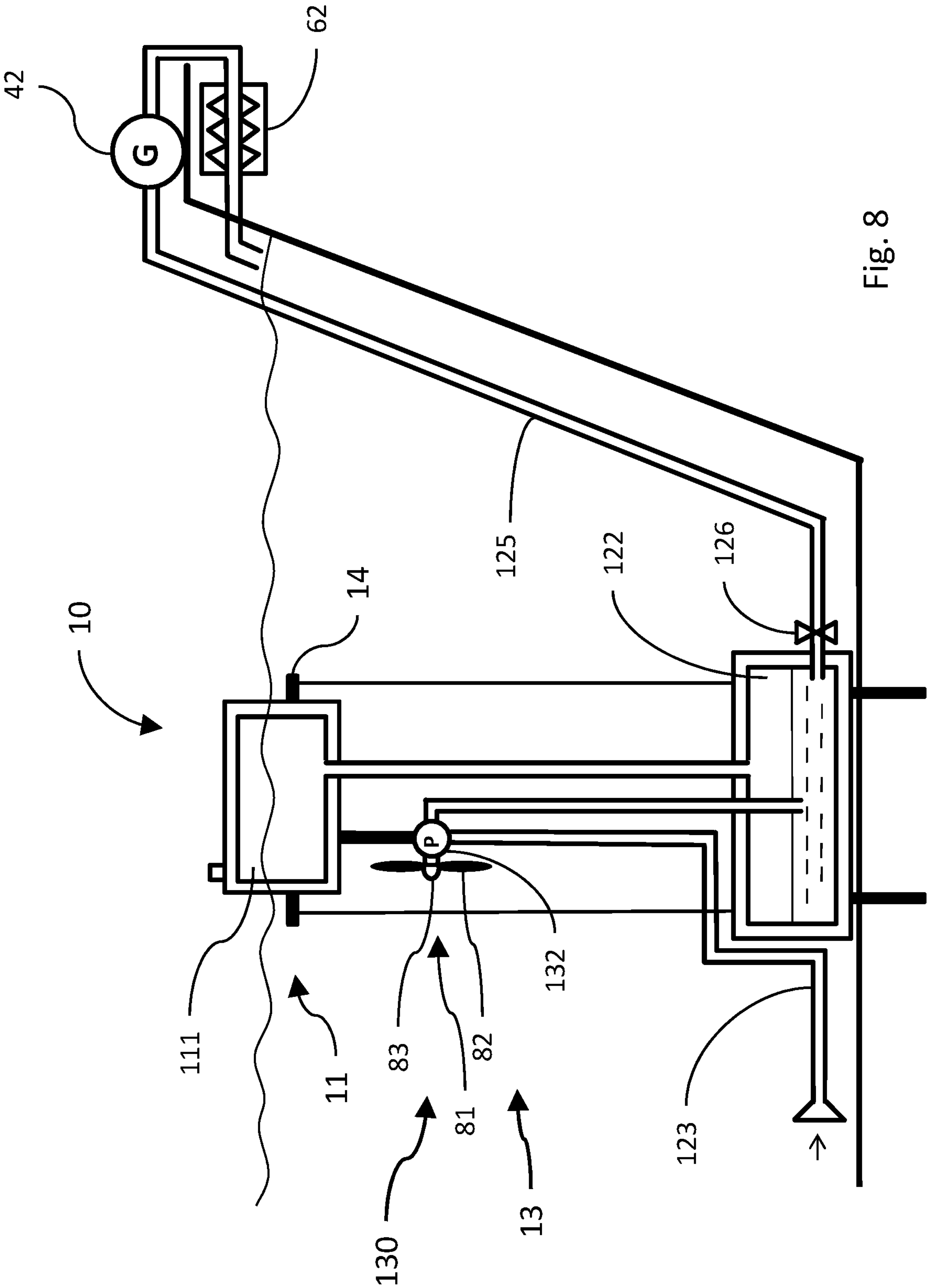
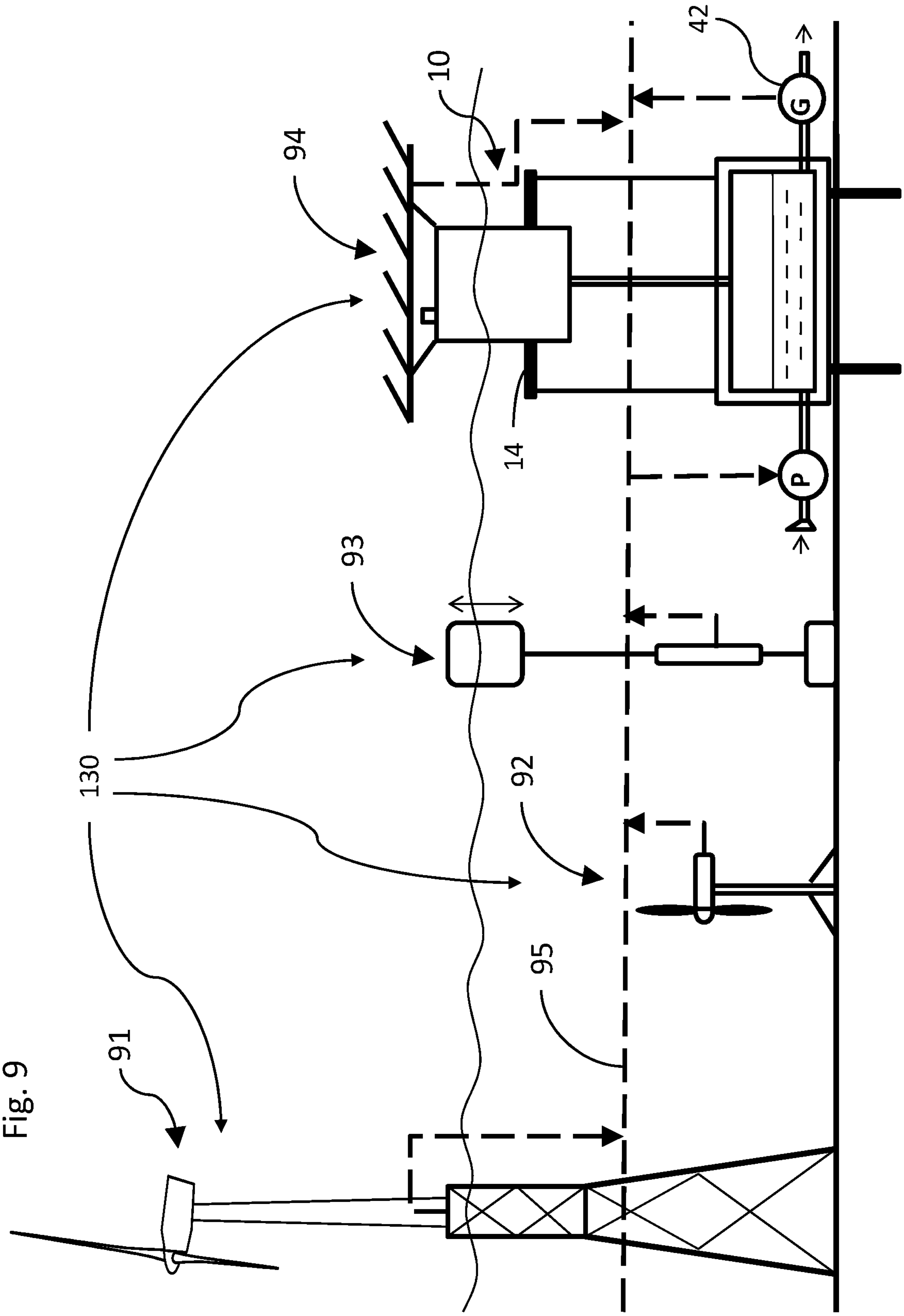


Fig. 8

Fig. 9



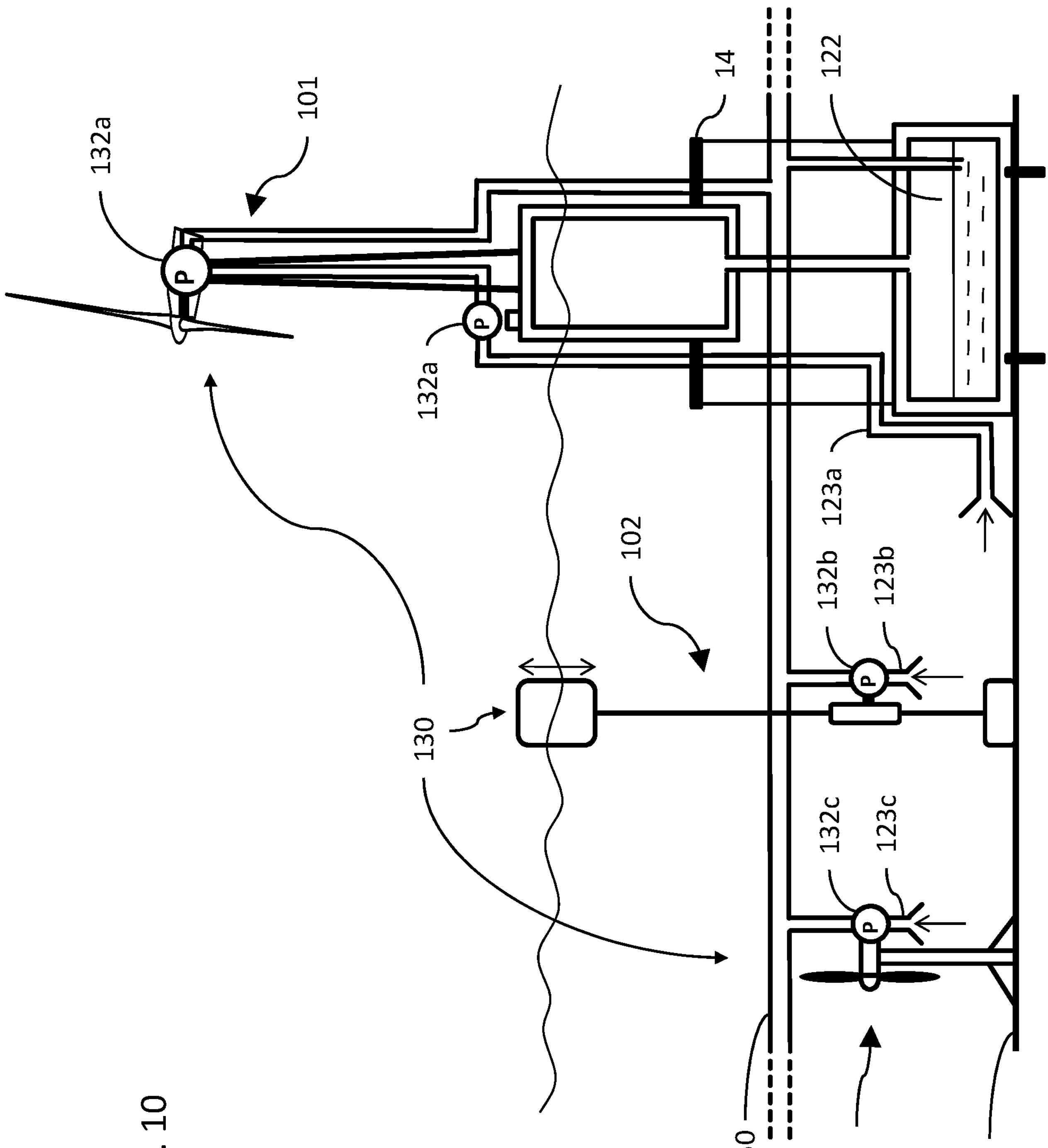

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Fig. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/IL2016/050100

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03B13/06 F03D9/17
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F03B F03D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	DE 10 2012 011492 A1 (SCHOPF WALTER [DE]) 12 December 2013 (2013-12-12) abstract paragraph [0005] - paragraph [0032] figures -----	1-25
Y	DE 10 2011 106040 A1 (DADGAR ARMIN [DE]) 27 December 2012 (2012-12-27) abstract paragraph [0001] - paragraph [0026] figures -----	1-25

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 May 2016	27/05/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Kolby, Lars

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 1 637 733 A1 (ELSAM AS [DK]) 22 March 2006 (2006-03-22)	1,2,14, 15,17, 20,21,23
A	abstract paragraph [0001] - paragraph [0058] figures	3,10-13, 16,18, 19,22, 24,25
A	CA 2 467 287 A1 (KUBB EDWARD MATT [CA]) 14 November 2005 (2005-11-14) page 6, paragraph 2 - page 18, paragraph 1 figures	1-25
A	DE 10 2012 100981 A1 (SCHRAMM RAINER [DE]) 8 August 2013 (2013-08-08) abstract paragraph [0041] - paragraph [0097] figures	1-25
A	US 4 206 608 A (BELL THOMAS J [US]) 10 June 1980 (1980-06-10) cited in the application abstract column 3, line 57 - column 8, line 32 figures	1-25

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IL2016/050100

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE 102012011492 A1	12-12-2013	NONE	
DE 102011106040 A1	27-12-2012	DE 102011106040 A1	27-12-2012
		EP 2724017 A1	30-04-2014
		WO 2013000809 A1	03-01-2013
		WO 2013000813 A1	03-01-2013
EP 1637733 A1	22-03-2006	AU 2005284511 A1	23-03-2006
		CA 2580554 A1	23-03-2006
		EP 1637733 A1	22-03-2006
		EP 1792080 A1	06-06-2007
		NZ 554512 A	27-11-2009
		US 2009129953 A1	21-05-2009
		WO 2006029633 A1	23-03-2006
		ZA 200703163 A	25-09-2008
CA 2467287 A1	14-11-2005	NONE	
DE 102012100981 A1	08-08-2013	DE 102012100981 A1	08-08-2013
		WO 2013117329 A1	15-08-2013
US 4206608 A	10-06-1980	NONE	