CLAIMS

What is claimed is:

1. A method, comprising:

increasing a pressure of at least a portion of a feed stream comprising a solvent and a solute to form a pressurized feed stream;

transporting a first reverse osmosis unit retentate inlet stream to a retentate side of a first reverse osmosis unit such that:

a first reverse osmosis unit retentate outlet stream exits the retentate side of the first reverse osmosis unit, the first reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the first reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the first reverse osmosis unit retentate inlet stream is transported from the retentate side of the first reverse osmosis unit, through an osmotic membrane of the first reverse osmosis unit, to a permeate side of the first reverse osmosis unit;

transporting a second reverse osmosis unit retentate inlet stream to a retentate side of a second reverse osmosis unit such that:

a second reverse osmosis unit retentate outlet stream exits the retentate side of the second reverse osmosis unit, the second reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the second reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the second reverse osmosis unit retentate inlet stream is transported from the retentate side of the second reverse osmosis unit, through an osmotic membrane of the second reverse osmosis unit, to a permeate side of the second reverse osmosis unit where the portion of the liquid forms some or all of a second reverse osmosis unit permeate outlet stream that is transported out of the permeate side of the second reverse osmosis unit;

reducing a pressure of at least a portion of the second reverse osmosis unit retentate outlet stream to form a reduced-pressure concentrate stream; and

using at least a portion of energy recovered from the reducing of the pressure of the at least a portion of the second reverse osmosis unit retentate outlet stream to increase a pressure of an energy recovery stream to form a pressurized energy recovery stream;

wherein:

the first reverse osmosis unit retentate inlet stream comprises at least a portion of the pressurized feed stream and at least a portion of the pressurized energy recovery stream;

the second reverse osmosis unit retentate inlet stream comprises at least a portion of the first reverse osmosis unit retentate outlet stream;

the energy recovery stream comprises at least a portion of the second reverse osmosis unit permeate outlet stream; and

(a) the energy recovery stream comprises a balancing stream comprising at least a portion of the feed stream, or

(b) the feed stream comprises a balancing stream comprising at least a portion of the second reverse osmosis unit permeate outlet stream.

2. The method of claim 1, wherein the energy recovery stream comprises a balancing stream comprising at least a portion of the feed stream.

3. The method of claim 1 or 2, further comprising discharging at least a portion of the reduced-pressure concentrate stream.

4. The method of any one of claims 1 to 3, further comprising adjusting a mass flow rate of the second reverse osmosis unit permeate outlet stream and/or the balancing stream such that the energy recovery stream has a mass flow rate within 20% of a mass flow rate of the at least a portion of the second reverse osmosis unit retentate outlet stream.

5. The method of any one of claims 1 to 4, wherein the first reverse osmosis unit retentate inlet stream comprises a recirculation stream comprising a first portion of the first reverse osmosis unit retentate outlet stream.

6. The method of any one of claims 1 to 5, wherein the step of using at least a portion of energy recovered from the reducing of the pressure of the at least a portion of the second reverse osmosis unit retentate outlet stream to increase a pressure of an energy recovery stream to form a pressurized energy recovery stream is performed using an energy recovery device.

7. The method of claim 6, wherein the energy recovery device is an isobaric energy recovery device.

8. The method of claim 6, wherein the energy recovery device is a turbine energy recovery device.

9. A method, comprising:

increasing a pressure of at least a portion of a feed stream comprising a solvent and a solute to form a pressurized feed stream;

transporting a first reverse osmosis unit retentate inlet stream to a retentate side of a first reverse osmosis unit such that:

a first reverse osmosis unit retentate outlet stream exits the retentate side of the first reverse osmosis unit, the first reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the first reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the first reverse osmosis unit retentate inlet stream is transported from the retentate side of the first reverse osmosis unit, through an osmotic membrane of the first reverse osmosis unit, to a permeate side of the first reverse osmosis unit;

transporting a second reverse osmosis unit retentate inlet stream to a retentate side of a second reverse osmosis unit such that:

a second reverse osmosis unit retentate outlet stream exits the retentate side of the second reverse osmosis unit, the second reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the second reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the second reverse osmosis unit retentate inlet stream is transported from the retentate side of the second reverse osmosis unit, through an osmotic membrane of the second reverse osmosis unit, to a permeate side of the second reverse osmosis unit where the portion of the liquid forms some or all of a second reverse osmosis unit permeate outlet stream that is transported out of the permeate side of the second reverse osmosis unit;

reducing a pressure of at least a portion of the second reverse osmosis unit retentate outlet stream to form a reduced-pressure concentrate stream; and

using at least a portion of energy recovered from the reducing of the pressure of the at least a portion of the second reverse osmosis unit retentate outlet stream to increase a pressure of an energy recovery stream to form a pressurized energy recovery stream;

wherein:

the first reverse osmosis unit retentate inlet stream comprises at least a portion of the pressurized feed stream, at least a portion of the pressurized energy recovery stream, and a recirculation stream comprising a first portion of the first reverse osmosis unit retentate outlet stream, wherein the recirculation stream is combined with the at least a portion of the pressurized energy recovery stream prior to incorporation into the first reverse osmosis unit retentate inlet stream;

the second reverse osmosis unit retentate inlet stream comprises a second portion of the first reverse osmosis unit retentate outlet stream; and

the energy recovery stream comprises at least a portion of the second reverse osmosis unit permeate outlet stream.

10. The method of claim 9, further comprising discharging at least a portion of the reduced-pressure concentrate stream.

11. The method of claim 9 or 10, further comprising increasing a pressure of the combination of the recirculation stream and the at least a portion of the pressurized energy recovery stream.

12. The method of any one of claims 9 to 11, wherein the step of using at least a portion of energy recovered from the reducing of the pressure of the at least a portion of the second reverse

osmosis unit retentate outlet stream to increase a pressure of an energy recovery stream to form a pressurized energy recovery stream is performed using an energy recovery device.

13. The method of claim 12, wherein the energy recovery device is an isobaric energy recovery device.

14. The method of claim 12, wherein the energy recovery device is a turbine energy recovery device.

15. The method of any one of claims 9 to 14, wherein the energy recovery stream comprises a balancing stream comprising at least a portion of the feed stream.

16. The method of claim 15, further comprising adjusting a mass flow rate of the second reverse osmosis unit permeate outlet stream and/or the balancing stream such that the energy recovery stream has a mass flow rate within 20% of a mass flow rate of the at least a portion of the second reverse osmosis unit retentate outlet stream.

17. An osmotic system, comprising:

a pump comprising:

a pump inlet, and

a pump outlet, wherein the pump is configured to eject a pressurized stream from the pump outlet;

a first reverse osmosis unit comprising at least one osmotic membrane defining a permeate side of the first reverse osmosis unit and a retentate side of the first reverse osmosis unit;

a second reverse osmosis unit comprising at least one osmotic membrane defining a permeate side of the second reverse osmosis unit and a retentate side of the second reverse osmosis unit; and

an energy recovery device comprising:

a high pressure inlet,

a low pressure inlet,

a high pressure outlet, and

a low pressure outlet;

wherein:

the retentate side of the first reverse osmosis unit is fluidically connected to the pump outlet;

the retentate side of the first reverse osmosis unit is fluidically connected to the retentate side of the second reverse osmosis unit;

the retentate side of the second reverse osmosis unit is fluidically connected to the high pressure inlet of the energy recovery device;

the retentate side of the first reverse osmosis unit is fluidically connected to the high pressure outlet of the energy recovery device;

the permeate side of the second reverse osmosis unit is fluidically connected to the low pressure inlet of the energy recovery device; and

the osmotic system is configured to combine a recirculation stream from a first portion of a first reverse osmosis unit retentate outlet stream exiting an outlet of the retentate side of the first reverse osmosis unit with a pressurized energy recovery stream exiting the high pressure outlet of the energy recovery device.

18. The osmotic system of claim 17, wherein the energy recovery device is an isobaric energy recovery device.

19. The osmotic system of claim 17 or 18, wherein the pump is a first pump, and the system further comprises a second pump comprising a second pump inlet and a second pump outlet, wherein the second pump inlet is fluidically connected to the high pressure outlet of the energy recovery device and the second pump outlet is fluidically connected to the retentate side of the first reverse osmosis unit.

20. The osmotic system of any one of claims 17 to 19, wherein the first reverse osmosis unit comprises a plurality of osmotic membranes.

21. The osmotic system of any one of claims 17 to 20, wherein the second reverse osmosis unit comprises a plurality of osmotic membranes.

22. A method, comprising:

increasing a pressure of at least a portion of a feed stream comprising a solvent and a solute to form a pressurized feed stream;

transporting a first reverse osmosis unit retentate inlet stream to a retentate side of a first reverse osmosis unit such that:

a first reverse osmosis unit retentate outlet stream exits the retentate side of the first reverse osmosis unit, the first reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the first reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the first reverse osmosis unit retentate inlet stream is transported from the retentate side of the first reverse osmosis unit, through an osmotic membrane of the first reverse osmosis unit, to a permeate side of the first reverse osmosis unit;

transporting a second reverse osmosis unit retentate inlet stream to a retentate side of a second reverse osmosis unit such that:

a second reverse osmosis unit retentate outlet stream exits the retentate side of the second reverse osmosis unit, the second reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the second reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the second reverse osmosis unit retentate inlet stream is transported from the retentate side of the second reverse osmosis unit, through an osmotic membrane of the second reverse osmosis unit, to a permeate side of the second reverse osmosis unit where the portion of the liquid forms some or all of a second reverse osmosis unit permeate outlet stream that is transported out of the permeate side of the second reverse osmosis unit;

reducing a pressure of at least a portion of the second reverse osmosis unit retentate outlet stream to form a reduced-pressure concentrate stream; and

using at least a portion of energy recovered from the reducing of the pressure of the at least a portion of the second reverse osmosis unit retentate outlet stream to increase a pressure of an energy recovery stream to form a pressurized energy recovery stream;

wherein:

the first reverse osmosis unit retentate inlet stream comprises at least a portion of the pressurized energy recovery stream;

the energy recovery stream comprises at least a portion of the pressurized feed stream and a recirculation stream comprising a first portion of the first reverse osmosis unit retentate outlet stream;

the second reverse osmosis unit retentate inlet stream comprises a second portion of the first reverse osmosis unit retentate outlet stream; and

the feed stream comprises at least a portion of the second reverse osmosis unit permeate outlet stream.

23. The method of claim 22, further comprising discharging at least a portion of the reduced-pressure concentrate stream.

24. The method of claim 22 or 23, wherein the step of using at least a portion of energy recovered from the reducing of the pressure of the at least a portion of the second reverse osmosis unit retentate outlet stream to increase a pressure of an energy recovery stream to form a pressurized energy recovery stream is performed using an energy recovery device.

25. The method of claim 24, wherein the energy recovery device is a turbine energy recovery device.

26. The method of any one of claims 22 to 25, further comprising adjusting a mass flow rate of the second reverse osmosis unit permeate outlet stream such that the energy recovery stream has a mass flow rate within 20% of a mass flow rate of the at least a portion of the second reverse osmosis unit retentate outlet stream.

27. A method, comprising:

increasing, during a first period of time and a second period of time, a pressure of at least a portion of a feed stream comprising a solvent and a solute to form a pressurized feed stream;

transporting, during the first period of time and the second period of time, a first reverse osmosis unit retentate inlet stream to a retentate side of a first reverse osmosis unit such that:

a first reverse osmosis unit retentate outlet stream exits the retentate side of the first reverse osmosis unit, the first reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the first reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the first reverse osmosis unit retentate inlet stream is transported from the retentate side of the first reverse osmosis unit, through an osmotic membrane of the first reverse osmosis unit, to a permeate side of the first reverse osmosis unit;

transporting, during at least the first period of time, a second reverse osmosis unit retentate inlet stream to a retentate side of a second reverse osmosis unit such that:

a second reverse osmosis unit retentate outlet stream exits the retentate side of the second reverse osmosis unit, the second reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the second reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the second reverse osmosis unit retentate inlet stream is transported from the retentate side of the second reverse osmosis unit, through an osmotic membrane of the second reverse osmosis unit, to a permeate side of the second reverse osmosis unit where the portion of the liquid forms some or all of a second reverse osmosis unit permeate outlet stream that is transported out of the permeate side of the second reverse osmosis unit;

reducing, during the first period of time and the second period of time, a pressure of a concentrate stream to form a reduced-pressure concentrate stream; and

using, during the first period of time and the second period of time, at least a portion of energy recovered from the reducing of the pressure of the concentrate stream to increase a pressure of an energy recovery stream to form a pressurized energy recovery stream;

wherein:

during at least the first period of time:

the second reverse osmosis unit retentate inlet stream comprises at least a portion of the first reverse osmosis unit retentate outlet stream;

the energy recovery stream comprises at least a portion of the second reverse osmosis unit permeate outlet stream; and

the concentrate stream comprises at least a portion of the second reverse osmosis unit retentate outlet stream;

during at least the second period of time:

the retentate side of the second reverse osmosis unit does not receive any portion of the first reverse osmosis unit retentate outlet stream or receives an amount of the first reverse osmosis unit retentate outlet stream that is at least 80 wt% less than an amount of the first reverse osmosis unit retentate outlet stream received by the retentate side of the second reverse osmosis unit during the first period of time, and the permeate side of the second reverse osmosis unit does not receive any portion of the reduced-pressure concentrate stream or receives an amount of the reduced-pressure concentrate stream that is at least 80 wt% less than an amount of the reduced-pressure concentrate stream received by the permeate side of the second reverse osmosis unit during the first period of time; and

the concentrate stream comprises at least a portion of a bypass stream comprising at least a portion of the first reverse osmosis unit retentate outlet stream; and

during both the first period of time and the second period of time:

the first reverse osmosis unit retentate inlet stream comprises at least a portion of the pressurized feed stream and at least a portion of the pressurized energy recovery stream.

28. The method of claim 27, wherein the concentrate stream does not comprise the at least a portion of the bypass stream during the first period of time.

29. The method of claim 27 or 28, wherein, during at least the second period of time, the energy recovery stream comprises a balancing stream comprising at least a portion of the feed stream.

30. The method of claim 29, wherein the energy recovery stream does not comprise the balancing stream comprising at least a portion of the feed stream during the first period of time.

31. The method of any one of claims 27 to 30, further comprising discharging at least a portion of the reduced-pressure concentrate stream.

32. The method of any one of claims 27 to 31, further comprising discharging a portion of the bypass stream via a bypass discharge stream.

33. The method of claim 32, further comprising adjusting a mass flow rate of the bypass stream and/or a mass flow rate of the bypass discharge stream such that a mass flow rate of the concentrate stream is within 20% of a mass flow rate of the energy recovery stream.

34. The method of any one of claims 27 to 33, further comprising combining a portion of the bypass stream with the reduced-pressure concentrate stream via a bypass discharge stream.

35. The method of any one of claims 27 to 34, further comprising adjusting a mass flow rate of the second reverse osmosis unit permeate outlet stream and/or the balancing stream such that the energy recovery stream has a mass flow rate within 20% of a mass flow rate of the at least a portion of the second reverse osmosis unit retentate outlet stream.

36. The method of any one of claims 27 to 35, wherein the first reverse osmosis unit retentate inlet stream comprises a recirculation stream comprising a first portion of the first reverse osmosis unit retentate outlet stream.

37. The method of any one of claims 27 to 36, wherein the step of using at least a portion of energy recovered from the reducing of the pressure of the at least a portion of the second reverse

osmosis unit retentate outlet stream to increase a pressure of an energy recovery stream to form a pressurized energy recovery stream is performed using an energy recovery device.

38. The method of claim 37, wherein the energy recovery device is an isobaric energy recovery device.

39. A method, comprising:

increasing, during a first period of time and a second period of time, a pressure of at least a portion of a feed stream comprising a solvent and a solute to form a pressurized feed stream;

transporting, during the first period of time and the second period of time, a first reverse osmosis unit retentate inlet stream to a retentate side of a first reverse osmosis unit such that:

a first reverse osmosis unit retentate outlet stream exits the retentate side of the first reverse osmosis unit, the first reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the first reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the first reverse osmosis unit retentate inlet stream is transported from the retentate side of the first reverse osmosis unit, through an osmotic membrane of the first reverse osmosis unit, to a permeate side of the first reverse osmosis unit;

transporting, during at least the first period of time, a second reverse osmosis unit retentate inlet stream to a retentate side of a second reverse osmosis unit such that:

a second reverse osmosis unit retentate outlet stream exits the retentate side of the second reverse osmosis unit, the second reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the second reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the second reverse osmosis unit retentate inlet stream is transported from the retentate side of the second reverse osmosis unit, through an osmotic membrane of the second reverse osmosis unit, to a permeate side of the second reverse osmosis unit where the portion of the liquid forms some or all of a second reverse osmosis unit permeate outlet stream that is transported out of the permeate side of the second reverse osmosis unit;

reducing, during the first period of time and the second period of time, a pressure of a concentrate stream to form a reduced-pressure concentrate stream; and

using, during the first period of time and the second period of time, at least a portion of energy recovered from the reducing of the pressure of the concentrate stream to increase a pressure of an energy recovery stream to form a pressurized energy recovery stream;

wherein:

during at least the first period of time:

the second reverse osmosis unit retentate inlet stream comprises at least a portion of the first reverse osmosis unit retentate outlet stream; and

the concentrate stream comprises at least a portion of the second reverse osmosis unit retentate outlet stream;

during at least the second period of time:

the retentate side of the second reverse osmosis unit does not receive any portion of the first reverse osmosis unit retentate outlet stream or receives an amount of the first reverse osmosis unit retentate outlet stream that is at least 80 wt% less than an amount of the first reverse osmosis unit retentate outlet stream received by the retentate side of the second reverse osmosis unit during the first period of time, and the permeate side of the second reverse osmosis unit does not receive any portion of the reduced-pressure concentrate stream or receives an amount of the reduced-pressure concentrate stream that is at least 80 wt% less than an amount of the reduced-pressure concentrate stream received by the permeate side of the second reverse osmosis unit during the first period of time; and

the concentrate stream comprises at least a portion of a bypass stream comprising at least a portion of the first reverse osmosis unit retentate outlet stream; and

during both the first period of time and the second period of time:

the energy recovery stream comprises at least a portion of the pressurized feed stream; and

the first reverse osmosis unit retentate inlet stream comprises at least a portion of the pressurized energy recovery stream.

40. The method of claim 39, wherein the concentrate stream comprises the at least a portion of the bypass stream during the first period of time.

41. The method of claim 39 or 40, wherein the concentrate stream does not comprise the at least a portion of the bypass stream during the first period of time.

42. The method of any one of claims 39 to 41, wherein the feed stream comprises at least a portion of the second reverse osmosis unit permeate outlet stream.

43. The method of any one of claims 39 to 42, further comprising discharging at least a portion of the reduced-pressure concentrate stream.

44. The method of any one of claims 39 to 43, further comprising increasing a pressure of the pressurized energy recovery stream with a pump.

45. The method of any one of claims 39 to 44, further comprising discharging a portion of the bypass stream via a bypass discharge stream.

46. The method of claim 45, further comprising adjusting a mass flow rate of the bypass stream and/or a mass flow rate of the bypass discharge stream such that a mass flow rate of the concentrate stream is within 20% of a mass flow rate of the energy recovery stream.

47. The method of any one of claims 39 to 46, further comprising combining a portion of the bypass stream with the reduced-pressure concentrate stream via a bypass discharge stream.

48. The method of any one of claims 39 to 47, wherein the energy recovery stream comprises a recirculation stream comprising a first portion of the first reverse osmosis unit retentate outlet stream.

49. The method of any one of claims 39 to 48, wherein the step of using at least a portion of energy recovered from the reducing of the pressure of the at least a portion of the second reverse osmosis unit retentate outlet stream to increase a pressure of an energy recovery stream to form a pressurized energy recovery stream is performed using an energy recovery device.

50. The method of claim 49, wherein the energy recovery device is an isobaric energy recovery device.

51. The method of claim 49, wherein the energy recovery device is a turbine energy recovery device.

52. A method, comprising:

increasing a pressure of at least a portion of a feed stream comprising a solvent and a solute to form a pressurized feed stream;

transporting a first reverse osmosis unit retentate inlet stream to a retentate side of a first reverse osmosis unit such that:

a first reverse osmosis unit retentate outlet stream exits the retentate side of the first reverse osmosis unit, the first reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the first reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the first reverse osmosis unit retentate inlet stream is transported from the retentate side of the first reverse osmosis unit, through an osmotic membrane of the first reverse osmosis unit, to a permeate side of the first reverse osmosis unit;

transporting a second reverse osmosis unit retentate inlet stream to a retentate side of a second reverse osmosis unit such that:

a second reverse osmosis unit retentate outlet stream exits the retentate side of the second reverse osmosis unit, the second reverse osmosis unit retentate outlet stream having an osmotic pressure that is greater than an osmotic pressure of the second reverse osmosis unit retentate inlet stream, and

at least a portion of liquid from the second reverse osmosis unit retentate inlet stream is transported from the retentate side of the second reverse osmosis unit, through an osmotic membrane of the second reverse osmosis unit, to a permeate side of the second reverse osmosis unit where the portion of the liquid forms some or all of a second reverse osmosis unit permeate outlet stream that is transported out of the permeate side of the second reverse osmosis unit;

reducing a pressure of at least a portion of the second reverse osmosis unit retentate outlet stream to form a reduced-pressure concentrate stream; and

using at least a portion of energy recovered from the reducing of the pressure of the at least a portion of the second reverse osmosis unit retentate outlet stream to increase a pressure of an energy recovery stream to form a pressurized energy recovery stream;

wherein:

the first reverse osmosis unit retentate inlet stream comprises at least a portion of the pressurized feed stream, at least a portion of the pressurized energy recovery stream, and at least a portion of the second reverse osmosis unit permeate outlet stream;

the second reverse osmosis unit retentate inlet stream comprises at least a portion of the first reverse osmosis unit retentate outlet stream;

the energy recovery stream comprises a balancing stream comprising at least a portion of the feed stream.