

Round-the-clock power supply and a sustainable economy via synergistic integration of solar thermal power and hydrogen processes

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We introduce a paradigm—“hydricity”—that involves the coproduction of hydrogen and electricity from solar thermal energy and their judicious use to enable a sustainable economy. We identify and implement synergistic integrations while improving each of the two individual processes. When the proposed integrated process is operated in a standalone, solely power production mode, the resulting solar water power cycle can generate electricity with unprecedented efficiencies of 40–46%. Similarly, in standalone hydrogen mode, pressurized hydrogen is produced at efficiencies approaching ~50%. In the coproduction mode, the coproduced hydrogen is stored for uninterrupted solar power production. When sunlight is unavailable, we envision that the stored hydrogen is used in a “turbine”-based hydrogen water power (H₂WP) cycle with the calculated hydrogen-to-electricity efficiency of 65–70%, which is comparable to the fuel cell efficiencies. The H₂WP cycle uses much of the same equipment as the solar water power cycle, reducing capital outlays. The overall sun-to-electricity efficiency of the hydricity process, averaged over a 24-h cycle, is shown to approach ~35%, which is nearly the efficiency attained by using the best multijunction photovoltaic cells along with batteries. In comparison, our proposed process has the following advantages: (i) It stores energy thermochemically with a two- to threefold higher density, (ii) coproduced hydrogen has alternate uses in transportation/chemical/petrochemical industries, and (iii) unlike batteries, the stored energy does not discharge over time and the storage medium does not degrade with repeated uses.

solar | electricity | hydrogen | solar thermal power | process synthesis

Diminishing fossil fuel resources and increasing atmospheric greenhouse gas levels raise the ever-growing interest in developing and implementing renewable energy conversion technologies and strategies to meet society’s energy needs (1–5). Among renewable energy sources, solar energy is prominent for its abundance. To put it into perspective, in 1.5 h 6.5×10^{20} J of solar energy reaches the earth, which is more than the primary energy consumed cumulatively by humans on the planet in 1 y ($\sim 5.4 \times 10^{20}$ J in 2013) (4, 6). However, harnessing solar energy for uninterrupted energy supply remains a challenge because it requires conversion systems to be integrated with efficient storage systems to overcome the inherent intermittency and uneven geographical distribution of solar irradiation.

Here, we introduce the concept of “hydricity” to address this challenge. We propose solar thermal coproduction of hydrogen and electricity and their subsequent synergistic use to support a sustainable economy. Hydricity not only leads to efficient production of solar electricity but also opens up many more possibilities: a sustainability roadmap. In the subsequent sections, we present an example hydricity process to supply uninterrupted electricity round-the-clock at a constant power rate with a calculated overall sun-to-electricity (OSTE) efficiency approaching 35%.

For the proper comparison of different solar power production processes, sun-to-electricity (STE) (*SI Appendix, Eq. S2*) and heat-to-electricity (*SI Appendix, Eq. S5*) efficiencies are the two main

metrics of interest. The STE efficiency refers to the fraction of incident solar energy that is recovered as the net electricity output and accounts for the losses in the solar concentrators and blackbody collection system. Heat-to-electricity efficiency refers to the fraction of process heat input that is recovered as the net electricity output and is a true measure of the efficiency of the power cycle. The third metric, OSTE efficiency (*SI Appendix, Eq. S4*), is the net STE efficiency for a constant power delivery round-the-clock—that is, over the average 24-h production accounting for energy storage and delivery of the stored energy. Hydrogen production cycles are evaluated based on sun-to-hydrogen efficiency, which refers to the fraction of incident solar energy that is recovered as the net hydrogen output based on its lower heating value (*SI Appendix, Eq. S10*).

Solar photovoltaic (PV) and solar thermal are the two main methods of solar power generation. Solar PV systems generate electricity using only a portion of the solar spectrum (7). However, PV systems are suitable for both diffuse and direct sunlight applications (8). To date, the maximum reported STE efficiencies for silicon-crystalline PV is 27.6%, single-junction gallium arsenide PV is 29.1%, and concentrator four-junction PV is 44.7% (9). Solar thermal systems use concentrators to absorb photons of all wavelengths in the incident spectrum as high-temperature heat (10, 11). Due to the use of optical concentrators, these systems can only be operated under direct sunlight, which imposes geographical limitations (12). Further, these systems are anticipated to be cost-effective only as large-scale power plants, owing to the capital costs of installing solar concentrators (12, 13). However, the highest STE

Significance

Diminishing fossil fuel resources and increasing atmospheric greenhouse gases present a compelling case for transitioning to a sustainable economy where all human needs can be met by using abundant solar energy. In this paper, we introduce “hydricity,” a paradigm that proposes synergistic coproduction of solar thermal power and hydrogen. We realize hydricity by judiciously integrating solar water power cycle, solar thermal hydrogen production techniques, and turbine-based hydrogen power cycle and by suitably improving each one for compatibility and beneficial interaction. The proposed hydricity concept presents a potential breakthrough solution for continuous and efficient power supply and also an exciting opportunity to envision and create a sustainable economy to meet all the human needs—namely, food, chemicals, transportation, heating, and electricity.

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We have investigated two solar hydrogen production systems: (i) direct thermal hydrogen production (28) and (ii) two-step hydrogen production (12, 27, 28). In the case of direct hydrogen production (*SI Appendix*, Fig. S8A), we simulated a membrane water-splitting reactor operating at the solar heat collection temperature. For two-step thermal hydrogen production (*SI Appendix*, Fig. S8B), we have simulated the $\text{Fe}_3\text{O}_4/\text{FeO}$ hydrogen production cycle (28, 31) as representative of the various known two-step water-splitting approaches. One of the features of the $\text{Fe}_3\text{O}_4/\text{FeO}$ cycle described by *SI Appendix*, Eqs. S8 and S9 is the gas–solid reactions involved that facilitate the separation of products (28).

Integration of the aforementioned solar hydrogen production methods and the modified power cycle leads to the hydricity concept, which is a synergistic platform to coproduce hydrogen and electricity from solar thermal energy. In one realization of the hydricity concept, the produced hydrogen is stored for later use, which results in an efficient uninterrupted solar thermal baseload power plant, or SWH₂P cycle. When solar energy is available, electricity, hydrogen, and oxygen are coproduced; then hydrogen is stored as compressed gas (350 bar and 298.1 K), and oxygen is stored in a liquid state (1.1 bar and 90.1 K). The SWH₂P cycle with two-step hydrogen production via $\text{FeO}/\text{Fe}_3\text{O}_4$ cycles is shown in Fig. 1A. We have also investigated the SWH₂P cycle with single-step hydrogen production via membrane reactor, the details of which are presented in *SI Appendix*. To demonstrate the benefit of a coproduction strategy, we have calculated the required exergy input to the SWH₂P cycle and compared it to the combined exergy required by the standalone solar water power cycle with 1-reheating (SWP-1) cycle and the standalone solar thermal hydrogen production process operating at 1,600 K solar heat collection temperature and using the $\text{FeO}/\text{Fe}_3\text{O}_4$ cycle (28) (*SI Appendix*, Table S7). The net exergy efficiency of the sum of standalone processes is 75.1%, whereas the net exergy efficiency of the integrated SWH₂P cycle is 81.1%. The efficiency improvement corresponds

to 8% less exergy input to produce exactly the same output, which is remarkable when used at GWh levels. This difference shows the benefit of coproducing hydrogen and electricity by using the proposed strategy and process. Furthermore, if for the standalone case the known direct solar thermal power cycle shown in *SI Appendix*, Fig. S1 (details in *SI Appendix*, Table S7) were to be used in lieu of the proposed SWP-1 cycle, the exergy benefit of the coproduction by the integrated SWH₂P cycle would increase to 11%. Please note that a further improvement in efficiency is anticipated with further optimization of the process.

Benefits Relative to the Standalone Processes

The advances that result in the high performance of the hydricity process are not exclusive to its coproduction operation mode. To demonstrate its benefits, we present two extreme cases of the hydricity process: high-pressure hydrogen production and electricity production.

Hydrogen is a much-needed chemical that can be produced from solar energy. However, to use and transport hydrogen, it must be compressed to very high pressures. The compression power is not considered as a part of the solar hydrogen production process and thus is not taken into account in calculating the hydrogen production efficiency. However, in reality, the compression work is substantial, and it is an inevitable part of the overall conversion process. The hydricity process can be easily modified to produce only high-pressure hydrogen as output; that is, the net electricity output of the process is reduced to zero (*SI Appendix*, Fig. S12). The result of producing the same amount of hydrogen at 350 bar by the hydrogen-only mode of the hydricity process is compared with the corresponding standalone case. The standalone case comprises a solar thermal hydrogen production process in conjunction with a solar thermal power plant to supply the electrical power needed for compression. Sun-to-hydrogen efficiency (*SI Appendix*, Eq. S10) of the hydrogen-only hydricity process is 50.3%, and the corresponding efficiency for the standalone case is ~46.5% with an efficient (STE efficiency, 30%) solar thermal power cycle and ~48.4% with the proposed modified power cycle. Hence, for the selected operating conditions and depending on the standalone solar thermal power cycle used, the solar energy savings for hydrogen production due to integration can be greater than 8%. More details of the process and results of various cases are given in *SI Appendix*, section 10.5 and Table S8, respectively.

The second case is the electricity-only hydricity process. The power cycle embedded in the SWH₂P cycle, referred to as the SWP cycle, can be operated as a standalone concentrating solar power plant (*SI Appendix*, Fig. S3). Concentrated solar power (CSP) technologies are extensively studied in the literature (32–34). The proposed SWP cycle is a central tower and direct steam cycle-type CSP plant.

The steam from HPT is reheated with solar energy and then further expanded in the medium-pressure turbine (MPT). This reheating between successive turbine expansions can be carried out multiple times. An attractive feature of the SWP cycle is the introduction of intermediate heat exchange between the discharge of the final MPT stage and the pressurized cold water stream. The proposed heat exchange scheme allows for the preservation of high-temperature heat in the system and rejection of heat from the system only at ambient temperature after expansion in the condensing turbine with a minimum exergy loss. This allows the cycle to operate efficiently and enables it to derive maximum benefit from reheating between expansion stages. Without the proposed intermediate heat exchange, the reheating stages may not accrue the same benefits, especially in high-temperature operating conditions.

Fig. 2 summarizes the estimated STE and heat-to-electricity efficiencies for the SWP cycle involving various reheating steps relative to the maximum achievable efficiency values as a function of the highest temperature used in the cycle (see *SI Appendix* for simulation details and process parameters used). The

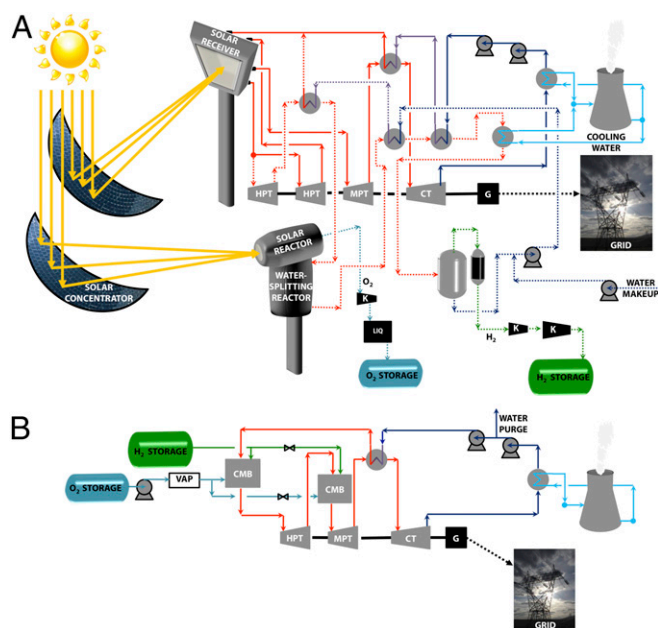


Fig. 1. (A) An example hydricity process: SWH₂P cycle with two-step hydrogen production using the $\text{FeO}/\text{Fe}_3\text{O}_4$ cycle. Solid lines represent streams that are solely involved in the electricity production (i.e., SWP-1). Dotted lines represent streams that are related to hydrogen production as well as electricity production. CT, condensing turbine; G, generator; HPT, high-pressure turbine; K, compressor; LIQ, liquefaction process; MPT, medium-pressure turbine. (B) H₂WP cycle, hydrogen oxy-combustion in water environment. CMB, hydrogen combustor.

biggest gain stems from using the first reheat (SWP with no reheat vs. SWP-1 with one reheat). Moreover, although the proposed power cycle enables the use of heat at higher temperatures, we see a major efficiency improvement in the range of 900 K to 1,400 K (Fig. 2).

Note that a significant fraction of the solar irradiation is lost in optical concentration and blackbody reradiation. Therefore, any improvement in solar heat collection technology will further improve the STE efficiency of the proposed cycles. For solar heat collection temperatures higher than 700 K, the STE efficiency of the SWP-1 cycle is estimated to be greater than 30%. This in itself is remarkable, as it allows for the possibility of achieving unprecedented STE efficiencies of greater than 30% at temperatures within the limits of operation of commercially available steam turbines. Additionally, if the materials of construction, particularly for the steam turbines, are modified to enable operation at higher temperatures above 1,250 K, the SWP cycles can achieve STE efficiencies that are greater than 40% (35, 36). Recent studies show that higher temperatures of up to 1,773 K are achievable for solar systems and gas turbines (35, 37, 38).

From Table 1 it is evident that the SWP-1 cycles integrated with batteries provide much higher OSTE efficiency values than current solar thermal technologies. Furthermore, the SWP-3 cycle reaches an OSTE efficiency equivalent to the most efficient multijunction PV systems. As mentioned, STE efficiency of the cycle can be further improved by adding solar reheating stages, albeit with diminishing STE efficiency improvements. Also, the improvement in turbine technologies would further improve the STE efficiency of SWP cycles.

Uninterrupted Efficient Power Supply Solution

During the period when solar energy is unavailable, we propose to use a turbine-based hydrogen power cycle (39), from now on called the hydrogen water power (H_2 WP) cycle, whereby hydrogen oxy-combustion is used to directly heat the working fluid. During the H_2 WP cycle, shown in Fig. 1B, hydrogen is combusted in a water environment. The hydrogen-to-electricity efficiency (based on the lower heating value of hydrogen) of the H_2 WP cycle is calculated to be 64.7% and 69.8% for turbine inlet temperatures between 1,600 K and 2,000 K. These efficiency values exceed the reported hydrogen-to-electricity efficiencies of standalone fuel cell systems, which are close to 60% (40). Because H_2 is compressed during the efficient operation of the integrated SWH₂P cycle, no compression is needed to provide high-pressure hydrogen to the combustor during H_2 WP cycle operation. This increases the power output of the H_2 WP cycle and reduces the amount of hydrogen needed during the periods when solar energy is unavailable, thus reducing the required storage

volume. In addition to the very high hydrogen-to-electricity efficiency, the process ensures the continuous operation of power generation equipment (e.g., turbines, condensers) used in the SWH₂P cycle by replacing solar heat with hydrogen combustion.

The proposed SWH₂P cycle combined with hydrogen oxy-combustion leads to an OSTE efficiency of 34.3% for a solar heat collection temperature of 1,600 K. This efficiency value is equivalent to the integration of the SWP-1 cycle at 1,600 K with a battery system with roundtrip efficiency of 77% and is comparable to the integration of SWP cycles with other large-scale energy storage methods such as PH (Table 1). We observe that although the hydrogen-to-electricity efficiency for the H_2 WP cycles is higher than 64.7%, the OSTE efficiency based on a 24-h cycle is nearly half that due to the solar energy requirement for the production and storage of hydrogen (3,305–3,469 m³/d) and oxygen (532–559 m³/d) as well as optical losses in the collection system during the operation of the SWH₂P cycle (100 MW power supply). The SWP-1 cycle integrated with batteries, particularly Na/S and Zn/Br flow types, achieves similar OSTE efficiency as the integrated SWH₂P– H_2 WP system. However, the latter has the potential to compete well with batteries, whereas it has higher volumetric energy density (3 GJ/m³ with only hydrogen storage, 2.6 GJ/m³ with hydrogen and oxygen storage) compared with that of batteries (0.6–1.3 GJ/m³) and no problem of relative degradation over the cycle life. Moreover, the gray energy (the energy used for the production of the equipment) will be much lower in the case of storage tanks than in the case of electrochemical batteries.

Effect of Operation Parameters and Other Technologies

Although optimal configurations and operating conditions for the presented processes are yet to be determined, we have investigated the effect of the major operating conditions on the performance of the processes (please refer to *SI Appendix, section 10.3.1* for details).

As follows from *SI Appendix, Eq. S2*, the STE efficiency is also sensitive to the solar concentration ratio. More concretely, *SI Appendix, Fig. S6* illustrates the STE efficiency of the SWP-1 cycle with 200 bar maximum pressure for various solar concentration ratios between 2,000 and 10,000. As the concentration ratio is increased, to realize associated benefit, the solar heat collection temperature must be increased. For example, at a solar heat collection temperature of 1,000 K, very little difference exists between a concentration ratio of 2,000 or higher, whereas at 1,600 K, one observes considerable improvement in efficiency as the concentration ratio is increased from 2,000 to 6,000. For the efficiencies listed in the paper, the solar concentration ratio was assumed to be 8,000, unless specified otherwise. However, for comparison, the sensitivity of the OSTE efficiency with respect to lower solar concentration ratios is shown in *SI Appendix, Fig. S11 A and B*.

Hydricity Vision

The transition to a sustainable economy requires preserving and advancing the current state of the civilization. The human race faces enormous challenges, not only because of a tremendous predicted increase in energy consumption as the world population continues to rise and economies develop but also because of the growing need to provide diverse forms of energy to meet society's demands for electricity, chemicals, heating, food, and transportation (6, 41, 42). In the current energy sector, production and delivery of all these needs are almost exclusively dependent on fossil resources. Assuring the best utilization of remaining fossil resources and designing an entire fossil-free energy network are the key objectives that must be adopted and systematically explored to transition to a sustainable economy. Using various renewable energy sources and suitable conversion processes is essential to achieve these objectives.

We envision that hydricity, efficient coproduction of hydrogen and electricity from the most abundant elements of nature—that is, solar energy and water—is the enabler of such a sustainability framework. We have demonstrated here, by rigorous process simulations, that hydrogen and electricity coproduced by using our processes can

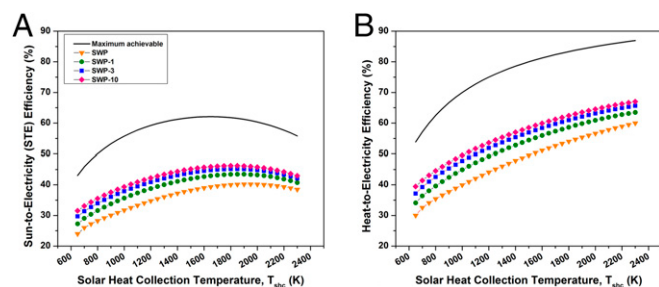


Fig. 2. Maximum achievable and SWP cycle efficiencies for a solar heat collection temperature range of 650–2,300 K with various numbers of reheating stages (1, 3, 10). (A) STE efficiency. (B) Heat-to-electricity efficiency. Maximum achievable efficiency calculation is explained in *SI Appendix, SI Materials and Methods*. Note that in A the maximum achievable efficiency accounts for the assumed 20% loss in the optical collection system and is not the pure maximum achievable thermodynamic efficiency.

provide uninterrupted electricity supply at a constant rate with unprecedented efficiency. Moreover, continuous solar power supply is only one of the applications of the hydricity process.

For a hydric economy, Fig. 3 presents a summary of possible allocations of resources for the production of various end-use forms of energy. To understand why a hydric economy is plausible, we first need to establish the position of hydrogen and electricity in the current energy sector. Hydrogen is the major carbon-free energy carrier and a key chemical that finds primary use in production and upgrading of fuels and chemicals (43, 44). In 2012, the United States consumed more than 1.07 EJ of energy-equivalent hydrogen, which was mainly produced from natural gas (45). Electricity is a secondary energy source that constitutes the greatest portion of our energy consumption. In 2011, ~13.9 EJ (~3,882 billion kWh) of net electricity was consumed in the United States (6). Furthermore, dependence on electricity is rapidly increasing, and among all energy forms, electricity consumption has the highest growth rate (6). A challenge in the use of electricity as a form of energy is that it cannot be stored as it is. It must be transformed to a different form of energy—that is, chemical, potential, etc.—which is oftentimes small scale, short-lived, and/or inefficient (16). Currently, the electricity sector adjusts the power production level to match the demand by using peak-shaving power plants, which are typically natural gas power plants. Such a strategy is unsustainable for intermittently available renewable energy sources.

The hydricity process can play a central role for all of the five sectors of energy consumption. For the electricity sector, solar thermal power will be supplied to the grid when solar energy is available. For continuous power supply, there are a number of options, which include (i) generating solar power in excess and storing the surplus using any large-scale energy storage method, (ii) storing a portion of the coproduced hydrogen to use in the same power cycle as described in the previous sections, (iii) distributing hydrogen to central or to local hydrogen power plants via hydrogen pipelines or as a blended mixture via existing natural gas pipelines, and (iv) supplementing the electricity need by using remaining fossil resources and other renewable energy sources such as wind power and geothermal. Central hydrogen power plants can be a gas turbine-based plant, hydrogen power cycle, or any kind of fuel cell plant. Electricity generation for a district or at the house level can be enabled by using fuel cells that use hydrogen from the hydrogen pipeline. Of course, when solar energy is available, generation and storage of electricity from PVs will also be an integral part of a hydric-based economy.

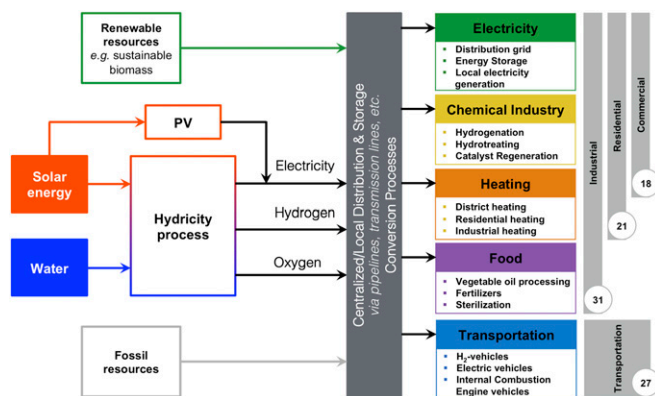


Fig. 3. Hydricity vision, examples of potential utilizations of a hydric process in various constituents of the energy sector. The 2013 US energy consumption figures for various energy sectors are shown in quadrillion British thermal units (BTUs) (6).

The chemical industry is one of the largest consumers of electricity, which can be supplied from a hydricity process using the strategies listed above. Moreover, hydrogen is an indispensable molecule for chemical industry. It is primarily used for hydrogenation, hydrotreating, and catalyst regeneration, which are common operations in all chemical plants. The essential component of all value chemicals is carbon, which can be supplied from biomass and remaining fossil resources. Furthermore, the replacement of fossil resources with renewable energy sources in the electricity sector and supply of hydrogen will allow the use of these resources as a valuable source of carbon for a significantly longer time.

Both residential and industrial settings consume a significant amount of energy as heat. Currently, natural gas and electricity are the dominant energy sources for providing heat. In this context, hydrogen from a hydricity process can substitute or supplement the natural gas for heating. Additionally, the direct use of high-temperature solar heat can reduce the need to use electricity and fuel for heating in a variety of applications, such as water heating and biomass gasification. We anticipate that integration of the hydricity process with other solar thermal processes will further increase the overall solar energy utilization efficiency.

The hydricity process could play an important role in different steps of the food industry, from growing the raw material to processing and preserving the end product. The production of all nitrogen and compound fertilizers requires the use of large quantities of hydrogen. Additionally, hydrogen is the major compound for the production of saturated fatty acids from vegetable oils.

The transportation sector is predominantly dependent on petroleum-derived liquid fuels. Using the estimates for sustainably available biomass for supplying transportation energy, it has been shown that the sustainably available biomass in the United States can supply no more than 30% of the current need of the US transportation sector with a standalone conversion process (46). The supply of hydrogen from a carbon-free energy source to an augmented process (47) will increase the carbon efficiency of the conversion process. Even the conversion of biomass using an augmented process (1), which uses the supply of hydrogen from a carbon-free energy source to improve carbon efficiency, has the potential to only supply approximately half of the current transportation sector's energy demand (46). For the remaining portion of the transportation need, such as for light duty vehicles, a technological change is indispensable and needed to reduce the liquid fuel demand. Electric vehicles and H₂ vehicles are among the most promising technologies, and the hydricity process is capable of meeting the remaining energy needs of the future sustainable transportation sector.

As briefly discussed in this section, hydricity has a central position in the sustainable energy picture. We believe that a hydric economy has the potential to consolidate all energy sources and provides a route to sustainability. Further details and in-depth analyses of each one of the pathways will be discussed in subsequent publications.

Conclusions

The proposed hydricity concept with the associated processes provides a promising route to sustainability. The key advances of hydricity process reside in multiple aspects: (i) a modification to the solar thermal power cycle that allows the efficient use of higher temperatures, resulting in not only efficient electric power production but also integration with H₂ production; (ii) the first proposal to synergistically integrate thermal power production and hydrogen/oxygen production through novel heat and mass integration between the two processes; and (iii) use of hydrogen to the power cycle, which, although maintaining the best efficiency, uses turbines that are also used during solar energy availability periods. The synergistic aspects of our proposed process reside in the high round-the-clock electricity and hydrogen generation efficiencies as well as subsequent hydrogen use.

The introduced solar thermal water power (SWP) cycle has the ability to efficiently use solar heat at higher temperatures and has the potential to generate electricity with efficiencies in the unprecedented range of 40–46% for solar heat collection temperatures above 1,250 K. The cycle also promises an efficiency of about 30% even at the relatively lower temperature of 700 K. These results are achieved with proper heat integration and reheats between turbine expansions. The ability to use higher solar heat collection temperatures allows for the integration of the SWP cycle with solar thermal hydrogen production techniques that coproduce hydrogen and oxygen.

In one realization of the hydricity concept, coproduced hydrogen is stored and then used for uninterrupted solar power production. A turbine-based H₂WP cycle, which uses hydrogen oxy-combustion in a pressurized water environment and runs the same power cycle as the one used for power production when solar energy is available, is used to produce power when solar energy is unavailable. The H₂WP cycle reaches a hydrogen-to-electricity efficiency of 65–70%, comparable to the highest reported hydrogen fuel cell efficiencies. For a 100-MW continuous power supply plant, the OSTE efficiency of the hydricity process, averaged over a 24-h cycle, is estimated to approach 35%, which is close to the efficiency attained by the best multijunction PV cells combined with batteries as a storage device but stores energy

thermo-chemically with a two- to threefold higher density. Furthermore, the hydricity concept not only presents a continuous and efficient power supply solution but also opens up other opportunities due to the coproduction of electricity and environmentally benign chemicals (hydrogen and oxygen) using elements of nature (water and solar energy). To appreciate the flexibility and versatility of hydricity, note that the coproduced hydrogen has many other uses in chemical industry, biofuel production, and transportation sector. We believe that a hydric economy based on the presented alliance of solar thermal power generation and hydrogen production has a potential to reshape the sustainability roadmap.

Methods

Well-known process system analysis methods in conjunction with the commercial software ASPEN Plus v.8.0 and MATLAB were used to perform all of the material and energy balances. The calculation details and results are provided in *SI Appendix*.

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