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WIND PROPULSION FOR SOLAR SHIP OPERATION

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ABSTRACT

Sea Transportation at moderate speeds is potentially by far the most energy-efficient mode of mass transportation at all – 10 times more efficient than road & rail and 100 times more so than air. Transport needs propulsion or traction, to overcome small friction or drag, which is usually provided by inefficient multiple energy transformation.

Wind, as a mechanical flow energy, already transformed from solar radiation, offers the unique chance of a short-cut to direct propulsion. Wind flow forces acting straight on air foils or sails can push the ship through the water. A broad range of suitable air foils in the form of soft 'Sail-Wings' or hard 'Wing Sails' is available for various wind propulsion applications.

Sea transportation, due to it's uniquely low energy demand, offers the chance of a high rate of supply by the low-density sources of wind flow and solar radiation. A proper combination of wind propulsion with solar energy and intelligent energy management on board could lead, step by step, to a future ship operation system with zero fossil fuel combustion and zero emission.

1. SUSTAINABLE OCEAN TRANSPORT?

Sustainability, as a criterion for human economic activities, was put forward some 300 years ago, when a German official for mining and forestry realised that the available forest capacity would be exhausted within a foreseeable period, if the exploitation would be continued without re-forestation. This obvious principle is well known in private-, and short-term housekeeping, but must be repeatedly recalled, if the long-term consequences will hit only the coming generations.

This simple message **that we have to pay our bill by ourselves,** instead of leaving it to our grand-children, is apparently not an issue in our present economic world. Our serious failures are, not to accept political responsibility over periods longer than a voting period, and that we treat future consequences of our economic activities as 'external costs', that can be ignored in our narrow-minded accounting system.

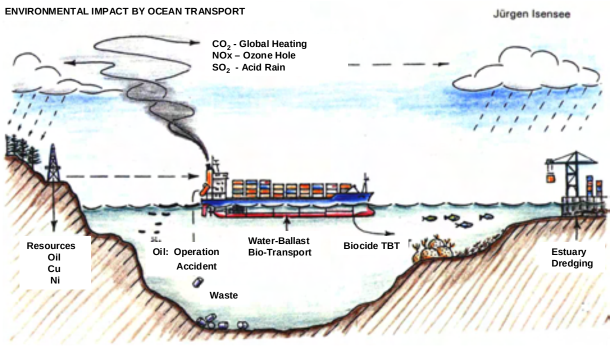

Figure1. Environmental impact by Ocean Transport.

Sea transportation has the greatest share in the global transport volume, but only a few percent in the global fuel burning. Isn't that **a prototype of sustainability?** But the issue in marine fuel is rather the quality than the quantity. Marine **residuary oil is so dirty** that it may not be used for road construction. The consequences are air pollution by CO_2, NO_X and SO_2, ocean pollution by oil emission due to operation, accidents and waste dumping. Additional problems are toxic emissions from anti-fouling paints, accelerating exhaustion of oil-, Cu- and Ni-resources and river estuary destruction by ever deeper dredging and harbour extension. All these problems are rapidly increasing with an accelerating growth of vessel numbers, sizes and service speeds.

A key issue of sustainable sea transport is the stepwise **reduction and final replacement of fossil fuel combustion** in order to reduce and eliminate the related emissions and to save the fossil resources. The consequent final objective of this development is a zero-emission ship operation technology powered by solar input energy sources. Marginal improvements in technical and operational efficiency alone are more than compensated by the global growth of transport volume

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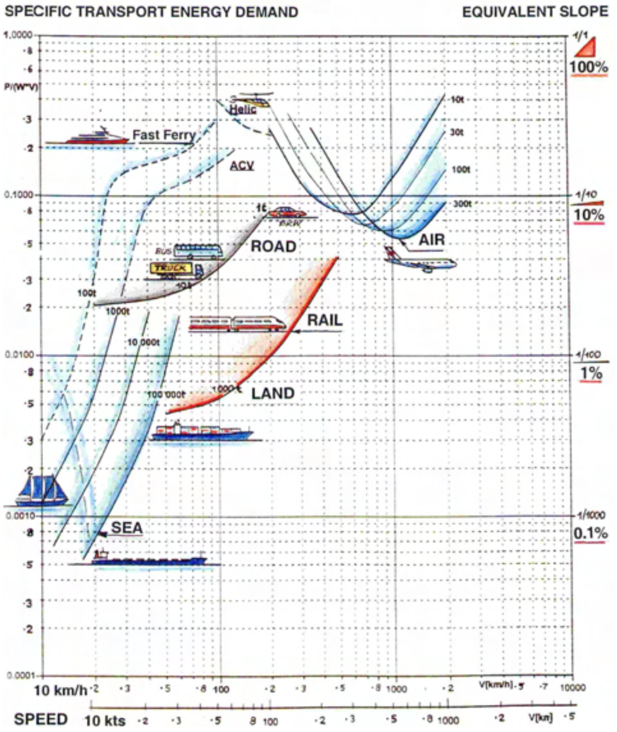


Figure 2. Specific Transport Energy Demand.

On the other hand, **Sea Transport** is potentially by far the **most energy-efficient** of all transport modes, **10 times more efficient than Land** Transport and **100 times more so than Air** Transport. If ‘zero emission’ transport is a real possibility, then shipping should be the first candidate to cover its low specific energy demand to a high percentage or entirely from low density renewable sources.

This is valid for mass transport at reasonable speeds. **Our present trend** however **to ever higher speeds** at sea, and ever faster ferries, can easily reach and overtake the specific energy demand of air transport, but at only 10% of air speed.

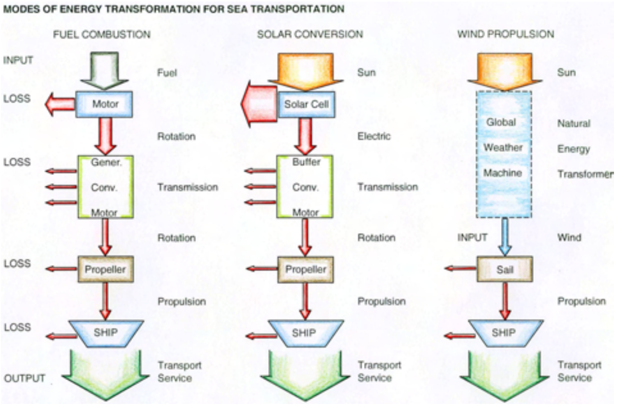


Figure 3. Modes of Energy Transformation for Ocean Transport.

Transport needs Propulsion or traction to overcome friction or ‘drag’. Propulsion is usually provided by **multiple energy transformation** (of chemical-, radiation-, thermal- ,fluid-flow-, rotational-, electrical-. . .-energy) with associated multiple **transformation losses** and low overall efficiency.

This is also valid for conversion of **solar radiation** into electrical and mechanical energy. This option is not only a problem of low density, low efficiency and high cost, but also seriously limited by the available area on board.

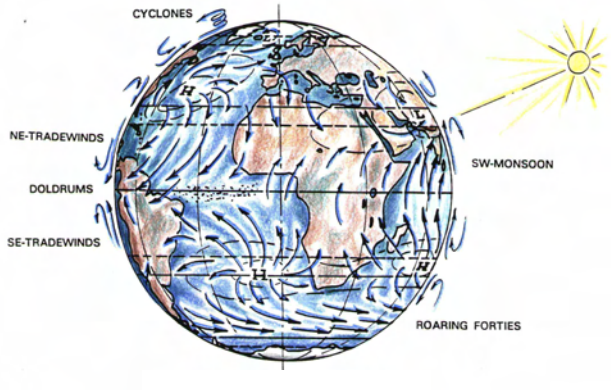


Figure 4. Global Wind Systems in July.

2. WIND PROPULSION

Wind is a mechanical fluid flow energy, which is already transformed from solar radiation by the global weather machine. This offers **the unique chance** of a **short-cut to direct propulsion**, without further transformation, by flow forces acting straight on **air-foils** to push the ship through the water **-** without ‘slip’.

This has been practiced, on an artisanal level, in shipping for at least 5000 years, until 100 years ago coal and oil burning engines driving propellers took over the role of propulsion. And this is just that period of 100 years, where our technical know-how developed explosively, in structural and mechanical engineering, in fluid-flow-, control- and information technology. We now understand, how wind-propulsion works and we could apply it much more efficiently, but we have used this new knowledge so far only for sports and recreation.

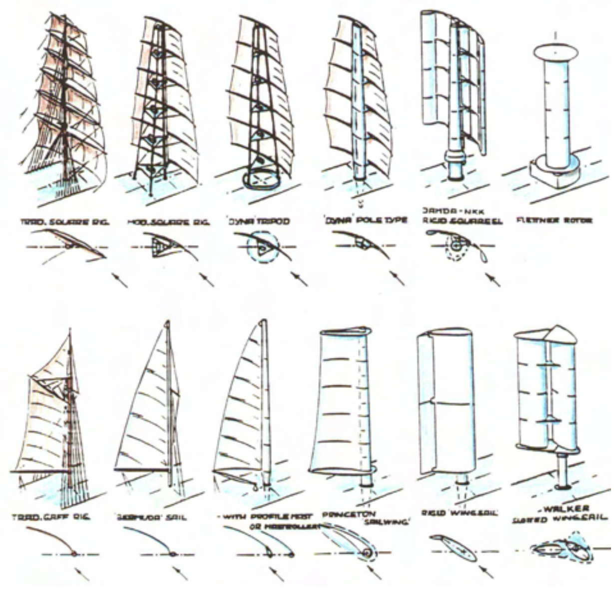


Fig. 5 Possible Developments of Traditional Sailing Rigs.

If we however consider this option for sustainable sea transport again, then we have a wide menu of technical systems available.

Air-Foils for Wind-Propulsion may be:

- **traditional soft Sails,**
- **advanced soft Sail-Wings,**
- **and rigid Wing-Sails**.

All of them have their special features and fields of application. Normal Sails are simple and well-known, Sail-Wings are soft, variable-area and variable–camber air-foils with improved lift-to-drag, and Wing-Sails are hard wings with flaps and even higher lift-to-drag.

Figure 6. Motor-Assisted Windship (INDOSAIL 1990)

Figure 7. Wind-Assisted Motorship (JAMDA 1980)

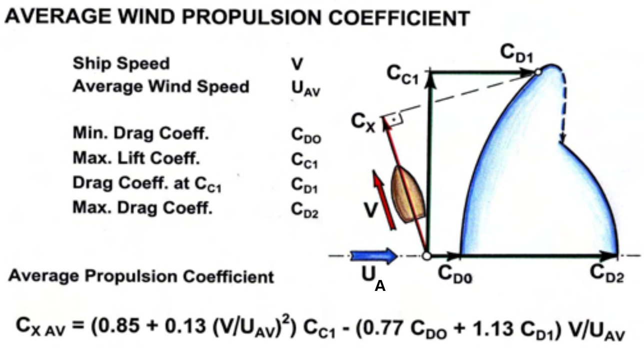
Since windships without motor are impossible in our days, a whole range of combination modes is considered, from: **Wind-Assisted Motorships** to
Motor-Assisted Windships.

For **wind-assistance to motorships** at constant service speed, the apparent relative wind conditions are concentrated to the forward sector, even when, on round trips, all headings to the true wind are equally frequent. This means that only **high Lift-to-Drag** options can provide efficient wind-assistance.

High-Lift options with correspondingly high induced drag, like short foil systems, suction- wings or rotors, are less suitable for this operation mode.

3. WIND-ASSISTANCE POTENTIAL

A simple parametric model for estimating the **wind-assistance potential** of different sails and foils is based on the main performance parameters of lifting foils as presented in the lift-versus-drag polar diagram: the coefficients of basic drag $\mathbf{C_{Do}}$, of maximal lift or 'cross-force' $\mathbf{C_{C1}}$ and the associated drag $\mathbf{C_{D1}}$.



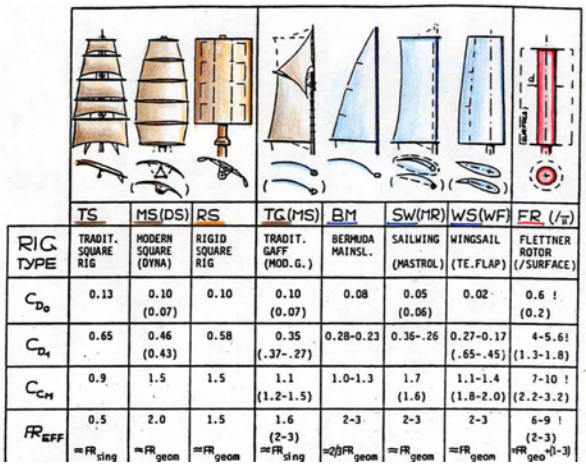
$$C_{X\,AV} = (0.85 + 0.13\,(V/U_{AV})^2)\,C_{C1} - (0.77\,C_{DO} + 1.13\,C_{D1})\,V/U_{AV}$$

Figure 8. Average Wind Propulsion Coefficient.

After systematic calculation of driving forces at constant ship speed **V** in all relevant wind speeds and relative courses, the results were averaged for Rayleigh-distributed wind-speeds with average $\mathbf{U_{AV}}$ and for all relative courses on round trips. The result is an annual average driving force coefficient $\mathbf{C_{XAV}}$ for operation in a wind climate of average wind speed $\mathbf{U_{AV}}$, approximated to:

$$\begin{aligned} C_{XAV} &\equiv F_{XAV}/(\rho/2\; U_{AV}^2\; A_S) \\ &\approx (0.85 + 0.13(V/U_{AV})^2)\; C_{C1} \\ &\quad - (0.77\; C_{Do} + 1.13\; C_{D1})\; V/U_{AV} \end{aligned}$$

This simple regression formula shows two terms: **a positive contribution** to driving force by maximal lift and **a negative term of loss,** due to the drag terms, which is increasing with relative ship speed to average wind. This is clearly underlining the importance of high lift and low drag for wind-assistance systems.



	TS	MS(DS)	RS	TG(MS)	BM	SW(MR)	WS(WF)	FR (/π)
RIG TYPE	TRADIT. SQUARE RIG	MODERN SQUARE (DYNA)	RIGID SQUARE RIG	TRADIT. GAFF (MOD.G.)	BERMUDA MAINSL.	SAILWING (MASTROL)	WINGSAIL (TE.FLAP)	FLETTNER ROTOR (/SURFACE)
C_{D_0}	0.13	0.10 (0.07)	0.10	0.10 (0.07)	0.08	0.05 (0.06)	0.02	0.6 ! (0.2)
C_{D_1}	0.65	0.46 (0.43)	0.58	0.35 (.37-.27)	0.28-0.23	0.36-.26	0.27-0.17 (.65-.45)	4-5.6! (1.3-1.8)
C_{CM}	0.9	1.5	1.5	1.1 (1.2-1.5)	1.0-1.3	1.7 (1.6)	1.1-1.4 (1.8-2.0)	7-10 ! (2.2-3.2)
AR_{EFF}	0.5 $\approx AR_{sing}$	2.0 $\approx AR_{geom}$	1.5 $\approx AR_{geom}$	1.6 (2-3) $\approx AR_{sing}$	2-3 $\approx 2/3 AR_{geom}$	2-3 $\approx AR_{geom}$	2-3 $\approx AR_{geom}$	6-9 ! (2-3) $\approx AR_{geo}+(1-3)$

Aerodynamic Parameters of Wind Propulsors

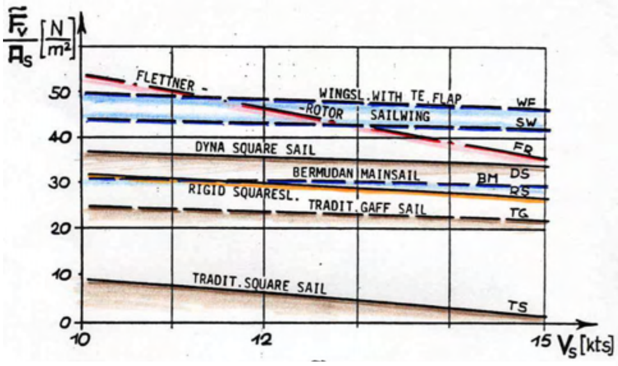


Figure 9. Average Driving Force F_{XAV}/A_S at an Average Windspeed U_{AV} = 15 kts.

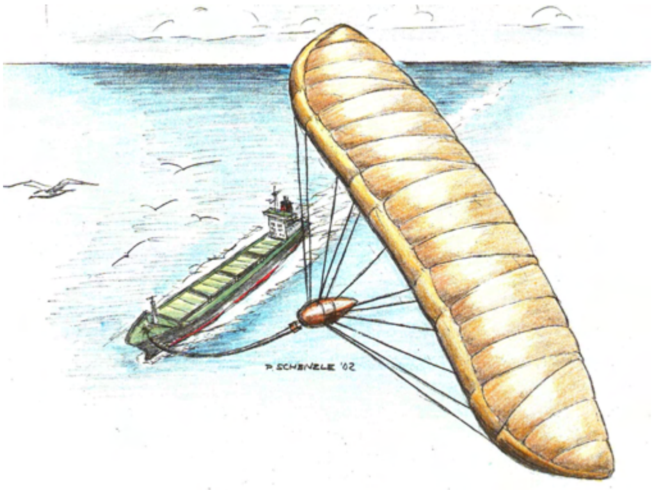


Figure 10. Kite Propulsion

Elevated Foils or Kites need no masts on deck and cause no heeling moments, they can be flown high up in stronger and more steady winds, but are also limited in forward relative winds and need to use their lift partly for elevation.

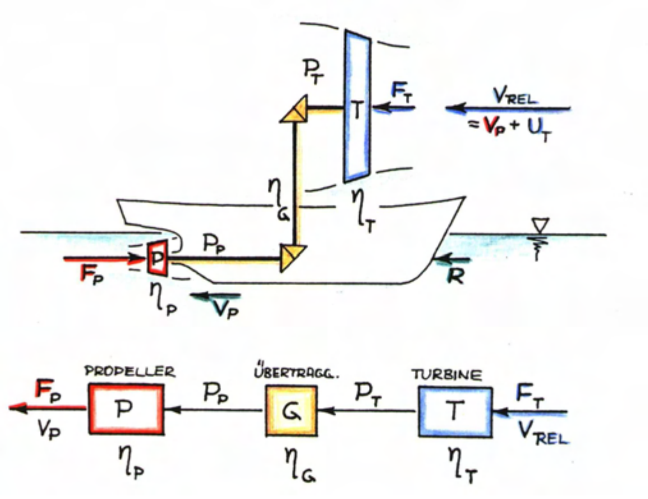


Figure 11. Windmill Propulsion

Windmills or –Turbines, driving a ship's propeller, are the only way of sailing **directly against the wind**, but the multiple energy transformation, in turbine, generator, motor and propeller, associated with multiple losses, make this system inferior to direct sail propulsion on all other courses.

4. STEPS TOWARDS SOLAR SHIP OPERATION

Even on motor-assisted wind-ships with **main-propulsion by the wind**, there is the **additional energy demand** for auxiliary propulsion and for board energy supply, which shall be covered in a sustainable way.

A first step away from fossil fuels could be introduced by regulations requiring **better fuel qualities** with less sulphur, like ashore. The higher price would stimulate more efficient technologies and operation modes (appropriate speeds). Next steps could be: **ethanol, natural gas and finally hydrogen** with progressively less emissions of particles, **SO_2, NO_X** and **CO_2**. The final stage could be a combination of photo-voltaic conversion on board with batteries and hydrogen as buffer storage medium and as additional bunker from shore-based solar- and wind-farms.

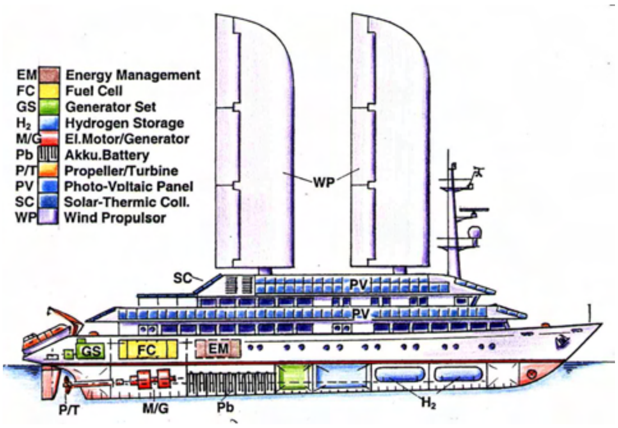


Figure 12. Elements of Solar Ship Operation

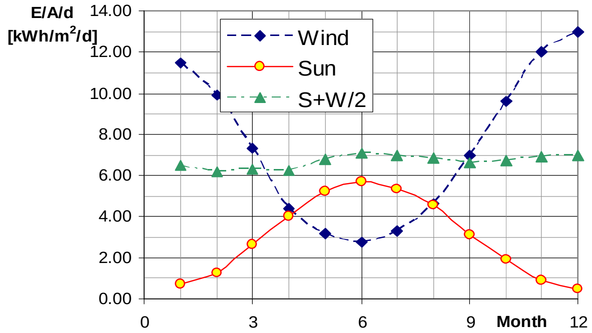


Figure 13. Seasonal Variation of Average Daily Solar and Wind Power Density (North Sea)

The local **combination of solar and wind energy** is supported also by the **negative correlation** of the immisions. In moderate latitudes it is clear that the solar maximum occurs in summer, while the wind is maximal in winter. A similar correlation holds in short-term weather between high-pressure and low-pressure periods, so that the sum of solar and wind input is significantly less variable than each of the components.

This cannot simply replace our present waste of cheap fossil fuel energy, but must be supplemented by **increased efficiency** of application and intelligent **energy management**. This includes also using our advanced tools for optimal weather routeing and port operations, to allow for seasonal and weather-dependent service speeds.

www.solarsailor.com

Figure 14. Sydney Solar Sailor Sightseeing Vessel

The **Solar Ship** will be a ship operation system combining the use of direct solar radiation with wind (and perhaps waves), with solar fuels and intelligent management of routeing, board- and port-operations. Projects in niches, like the 'Sydney Solar Sailor', show that this is not only a future dream but a realistic technical possibility.

Whether or not (and when) we will develop **Sustainable Technology, like the 'Solar Ship'** as an example, is not really a technical or economical question. It is rather a problem of our mental readiness to **accept our responsibility for the future** and start sailing up-wind against the present trend towards ever faster destruction of the unique and precious living space of a growing mankind.

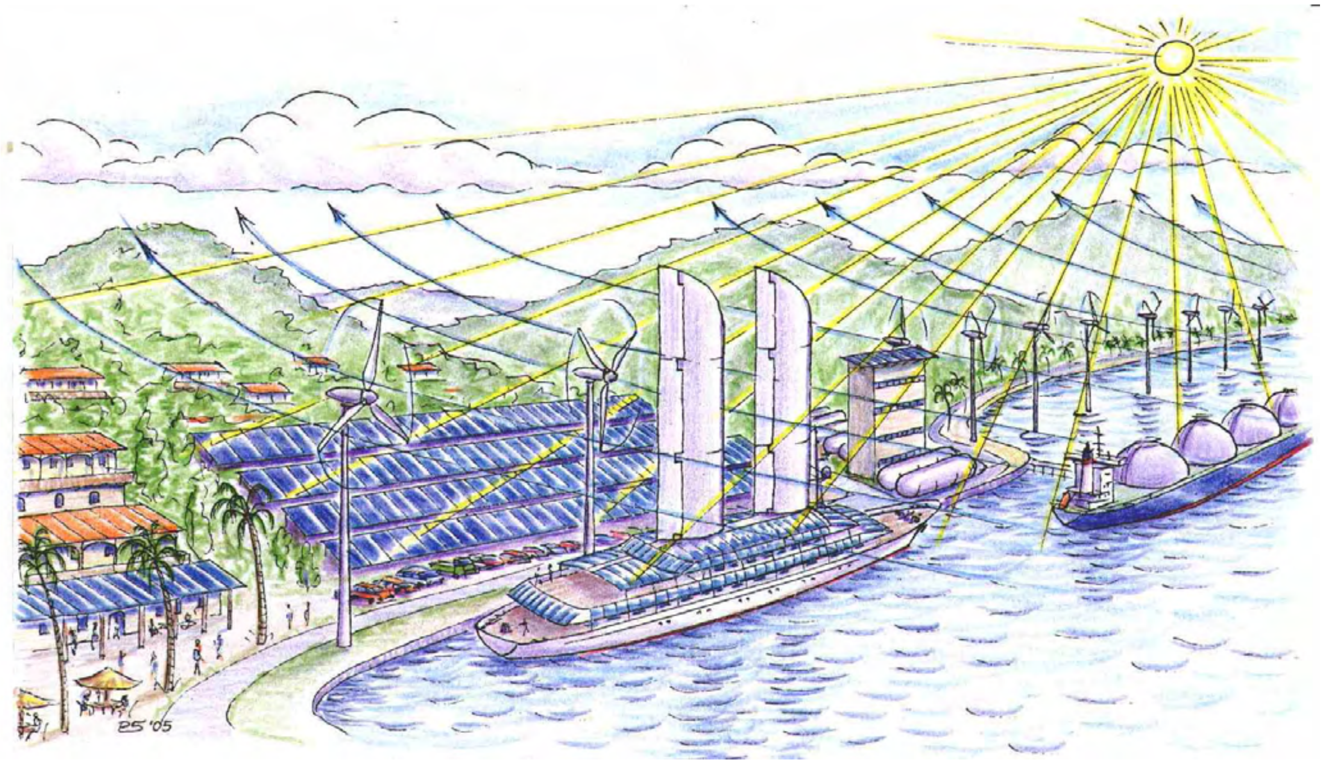


Figure 15. A Solar Input Economy