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Generic Energy Matching Model and Figure of Matching Algorithm for Combined Renewable Energy Systems

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ABSTRACT

In this paper the Energy Matching Model and Figure of Matching Algorithm which originally was dedicated only to photovoltaic (PV) systems [1] are extended towards a Model and Algorithm suitable for combined systems which are a result of integration of two or more renewable energy sources into one. The systems under investigation will range from mobile portable devices up to the large renewable energy system conceivably to be applied at the Afsluitdijk (Closure-dike) in the north of the Netherlands. This Afsluitdijk is the major dam in the Netherlands, damming off the Zuiderzee, a salt water inlet of the North Sea and turning it into the fresh water lake of the IJsselmeer.
The energy chain of power supplies based on a combination of renewable energy sources can be modeled by using one generic Energy Matching Model as starting point.

Keywords: Energy Matching Model, Figure of Matching Algorithm, Integration of Renewable Energy Systems.

1. INTRODUCTION

In a Sustainable Energy Society it is important that all harnessed energy is used as effective as possible. To achieve this efficiency goal in PV powered systems, a novel and generic Energy Matching Model and associated Figure of Matching Algorithm have been developed [1]. To cope with the exploding energy demand in the world it would be recommendable to exploit not just one renewable energy source but to use all appropriate ones simultaneously. So there is a need for a model and algorithm that can be used in combinations of two or more renewable energy sources. Therefore as a further development, the original Model and Algorithm developed for PV systems were extended to other renewable energy sources [2] as well as to integrated energy sources [3,4].
This paper presents new applications and innovations as a result of cross-fertilization among Energy, Informatics and Cybernetics. Therefore, conform the purpose of the EIC 2008 symposium; it demonstrates the increasingly interrelated relation between the three, complementing each other in theory and practice and presents an even further extension of the original Model and Algorithm.
The Model will describe an integrated system consisting of two or more energy chains operated in parallel.
The Figure of Matching (FM) Algorithm will be used to analyze and quantify how well the matching between the elements in each of the combined energy chains could be achieved.

2. THE ENERGY MATCHING MODEL

2.1 The original Energy Matching Model for PV powered system

In the original model dedicated to match the energy chain of a PV powered product, the main components are the incident light, the PV cell as light to electricity converter, an electrical storage medium and the application of the product.
The spectrum and power of the light source depend on the location of use such as indoors or outdoors, location on the earth globe such as near the equator or near the poles, time of the day and season. In fact the light source is dependent on the user context.

The main components of an energy chain of a PV powered product can be presented in an Energy Matching Model as presented in Figure 1.
The Energy Matching takes place at the Matching Interfaces MI:1, MI:2 and MI:3.
Additional factors that influence the Energy Matching of the energy chain are Mechanical Dimensions, Ergonomics, Temperature, Humidity and other Environmental parameters.
The User Context in this model is both starting point and end point of the matching loop.

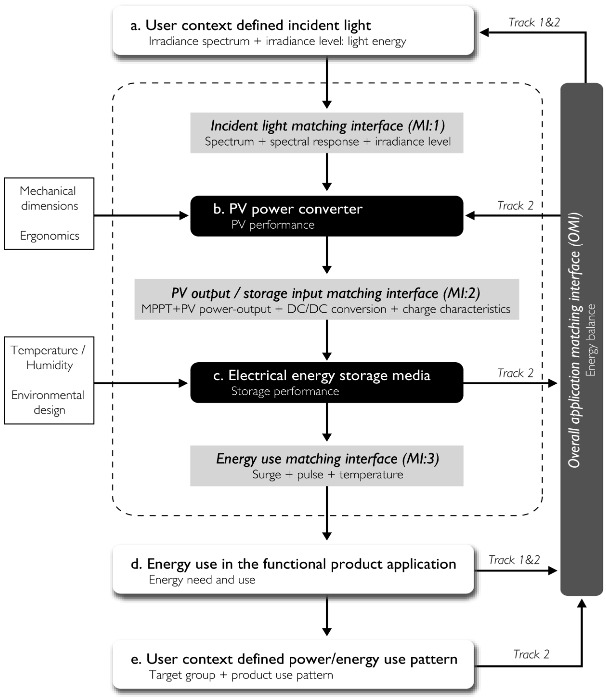

Figure 1: The Energy Matching model of the energy chain of a PV powered product

2.2 The Generic Model

Whether based on photovoltaics (PV), human power (HP), fuel cells (FC) or wind energy (WE), a energy chain of a product can be structured into a model comprised of some kind of energy source, an energy carrier + conversion part and an energy storage part and an energy consuming application [2].
So to simplify the steps towards the use of a generic Energy Matching Model for combined renewable power supplies, each of the individual energy chains in the combination will be divided as described in Figure 2. In addition to analyze the interaction and matching between these basic structural elements, some matching interfaces (MI: 1 till 3) can be defined.

Energy source + carrier
Energy carrier – converter matching interface MI:1
Energy Converter
Energy converter – storage matching interface MI:2
Energy storage
Energy storage – application matching interface MI:3
Application

Figure 2: Basic structure elements and matching interfaces of a generic Energy Matching Model of the energy chain of a product with a renewable energy power source.

2.2.1 The energy source:

Photovoltaics (PV): The energy source is the sun or an artificial light source (lamp).
Human power (HP): The human body.
Fuel cells (FC): Hydrogen atoms, however since these atoms as such are not readily available to be put into fuel cells, some effort (energy) must be put into the gathering, chemical processing and packaging of hydrogen compounds.
Wind (WE): The energy source is the wind as result of pressure differences in the atmosphere.

2.2.2 The energy carrier and the energy converter:

PV: The energy carrier is light which is converted by a photovoltaic cell directly into electrical power.
Light power is characterized by the intensity or irradiance expressed in W/m^2 and the spectrum of the light expressed in $W/m^2/nm$. For an optimal matching comparison, the light spectral response of the PV cell under investigation is correlated with the irradiance spectrum.
HP: The energy carrier is mechanical human muscle force and body heat which can be converted with the aid of a generator or converter into electrical power. Due to the small power yield harnessed with body heat, human power (HP) is generally only associated with mechanical muscle force.
FC: The energy carrier is hydrogen which is converted together with oxygen by the aid of a fuel cell into electrical power. Hydrogen atoms are extracted from the stored ‘fuel’ such as hydrogen gas, methanol or other hydrogen compounds. The oxygen is either extracted from the air or stored separately.
WE: The energy carrier is the mechanical wind force which can be converted, with the rotor blades of a wind turbine, into a torque or turning force which, with the aid of an electro-generator, can be converted into electrical power. Wind power is characterized by the density of the air, wind speed in m/s, wind speed ‘spectrum’ or statistical distribution at the location of interest, the so-called Weibull probability density distribution [5]. For optimal matching comparison, the wind speed response of the generator is correlated with the Weibull distribution. To compensate for variation in turbine + rotor blade design, the compared wind turbines are all operated at the effective available wind power input limit in accordance to Betz’ law.

2.2.3 The energy storage media:

Although the electrical energy generated by PV cells could either be used directly in an application or stored as electro-chemical energy in batteries or in a capacitor [6], PV conversion will generally be associated with electrical energy storage media. However in cases in which photovoltaics is used to aid electrolysis, there will also be hydrogen gas storage, and sometimes even separate oxygen gas storage involved. Combining the two gasses in a fuel cell would yield again electricity.
HP could be stored as potential energy in a spring or in compressed gas or as kinetic energy in a flywheel. After conversion by an electric generator, it can be stored as electrical energy in a battery.
The ‘fuel’ and energy carrier for the FC is stored as a hydrogen compound in a container. In this case there is a distinct difference between storage of electrical energy and storage of the energy carrier. In case one compares

electrical energy storage densities of various technologies this difference should be noticed and taken into account
WE could be stored as electrical energy in batteries and (super) capacitors. For large systems such as the Afsluitdijk, water storage pools or water towers could be considered. This Afsluitdijk is a major dam in the north of the Netherlands, enclosing the Zuiderzee. This salt water inlet of the North Sea was turned by the dam into a fresh water lake, the IJsselmeer.

2.2.4 The energy consuming application:

There will be various energy consuming applications ranging from actual use of a product to energy harnessed to be distributed by a kind of grid.

2.3 Matching of non-energy related parameters

In finding the optimal matching between the elements of an energy chain, other parameters beside energy could be significant. These other parameters are boundary conditions dictated by the user context. To take the contributions of these other parameters into account, weight factors' could be implemented at the matching interfaces indicating the amount of deviation from the ideal or required parameter value. The larger the deviation, the less well the matching will be and the more the transfer efficiency between the elements will be reduced by the weight factor.
For example, due to the requirement of being portable, the weight of the product is an important parameter. The deviation of the ideal or maximum weight can be introduced as weight factor. This could have impact on the choice of the energy storage system. As a result the lighter Li-Ion battery will be preferred to the heavy lead acid one. This choice can be quantified with the Figure of Matching algorithm that includes weight factors.

3. FIGURE OF MATCHING ALGORITHM

For optimal matching within the energy chain of a PV powered product the light source under consideration should be properly matched with the type of PV cell. This can be calculated with the Figure of Matching Algorithm as presented in Table 1.

Light Source / PV cell Technology	$FM_{Spectral}$ with AM 1.5	$FM_{Spectral}$ with TLD	$FM_{Spectral}$ with Incandescent
c-Si	14,9 %	14,6 %	10,9 %
a-Si	8,3 %	17,6 %	2,7 %
mc-Si	13,4 %	13,6 %	9,3 %
CIS	15,8 %	16,8 %	10,8 %
DSC	7,5 %	19,3 %	2,3 %

Table I: Figure of Matching of various PV cells irradiated with several light sources [1]

The Figure of Matching Algorithm can be seen as a clear example of cross-fertilization among Energy, Informatics and Cybernetics. This Figure of Matching Algorithm is a combination, adaptation and extension of two analytical methods, namely the Stimulus – Response Transfer Concept and the Correlation Concept known from the general theory of Information Transfer.

With this Algorithm, the correlation between two consecutive elements in an energy chain can be investigated. In particular, the output of the first one is correlated with the Step Response of the second. With this correlation, according to the theory of transmission lines, the power transfer efficiency between the two is established. Having determined the Step Response of one element p, R_{Step-p}, the impact of various stimuli of the influencing elements on this element p can be compared with the aid of the Figure of Matching algorithm as presented in Figure 3. Now the optimal matched pair can be selected.

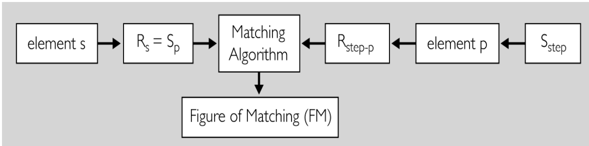

Figure 3 The Figure of Matching (FM) algorithm applied between two consecutive elements s and p in the energy chain [1].

Since the Figure of Matching is a quotient of the correlation and the overall stimulus S it can be regarded as a normalized correlation. The result of the Figure of Matching will be a fraction or in case it is normalized to 100%, it will indicate the % transfer efficiency between two consecutive elements in an energy chain.

4. COMBINED ENERGY SYSTEMS

4.1 The Model of combined energy systems:
In a system powered by a combination of two or more energy sources, each individual chain is matched inside itself and in addition with the other. The combined energy systems can be operational together simultaneously or alternating. In this paper the focus will be on a system powered by the combination of two energy systems namely PV and wind energy, however since the energy model used is generic, it can be extended to any other combination or number of energy systems. PV and wind energy will be complementary. For example in this combination if there is less or even no light, energy can be harnessed by wind energy. If there is neither light nor wind a fallback on electrical storage should be provided. The energy chain of power supplies based on combined renewable energy sources can be modeled by using one generic Energy Matching Model as starting point.
So the basic structural elements of a combined Energy Matching Model for renewable power supplies are presented in Figure 4. Here the Matching of the combined Interfaces (IMI: a, b and c) will take into account the actual interferences or enhancements as result of combining two or more energy chains.

Energy source + carrier 1	**IMI: a**	**Energy source + carrier 2**
Energy carrier – converter matching interface MI:1.1		**Energy carrier – converter matching interface MI:2.1**
Energy Converter 1	**IMI: b**	**Energy Converter 2**
Energy converter – storage matching interface MI:1.2		**Energy converter – storage matching interface MI:2.2**
Energy storage 1	**IMI: c**	**Energy storage 2**
Energy storage – application matching interface MI:1.3		**Energy storage – application matching interface MI:2.3**
Application		

Figure 4: Basic structure elements and matching interfaces of a combined Energy Matching Model of two energy chains, each with a renewable energy power source

4.2 Figure of Matching algorithm and the Energy Matching Model of combined systems

The Figure of Matching algorithm is based on power transmission lines. Therefore in the first place it can be used to match the elements in the individual energy chains in the combined energy system. However between the energy chains which constitute the combined energy system there will be no power transfer as such, therefore the Figure of Matching Algorithm can not be used.

To match the energy chains optimally with each other, at least the following steps have to be taken which can also be regarded as a matter of good engineering practice:

1. The integration of several energy chains shall not introduce a reduction of performance at one of the participating ones.
2. The introduction of control electronics shall not counterbalance the benefit of putting two or more energy chains in one system in parallel.
3. The energy sources should if possible be complementary to each other resulting in a continuous power generation over a period of time, e.g. 24 hours, a month, a complete year and therefore compensating for the various climate conditions and seasons.

5. APPLICATIONS OF THE ENERGY MATCHING MODEL AND ASSOCIATED FIGURE OF MATCHING ALGORITHM IN COMBINED SYSTEMS

5.1 Existing combinations

As an example the combination of photovoltaic and wind energy is presented. Such combinations are already operational and applied for street lights [7] and battery recharge points for mobile products as can be seen in Figure 5.

In the first example (a) which uses a 'Gyro type' turbine, the rotor of the wind turbine is placed above the PV panels. In the second example (b) the situation is reversed. Both wind turbines use a vertical rotation axis to match the vertical lamp pole design. For optimal matching at Integration Matching Interface IMI:a between the energy sources and carriers of the two energy chains, the later solution (b) avoids shadows on the PV panels.

a) b)

Figure 5: Examples of street lights and recharge points for mobile products in Tokyo, Japan.

5.2 The energy carrier – converter matching (MI: 1.1 and MI: 2.1)

For the photovoltaic (PV) system, the Figure of Matching is used in optimizing the matching between the light spectrum of the incident light flux (S_p) coming from a light source (element s) and the spectral Step Response (R_{Step-p}) which is the spectral response of the PV cell (element p) as in the matching interface MI:1.1.

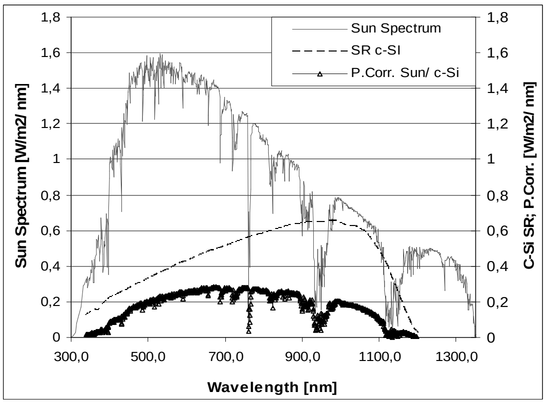

Figure 6: The sun's spectrum at sea level, the spectral response (SR) of a crystalline silicon (c-Si) PV cell and the power correlation between the Sun spectrum and a c-Si PV cell [1].

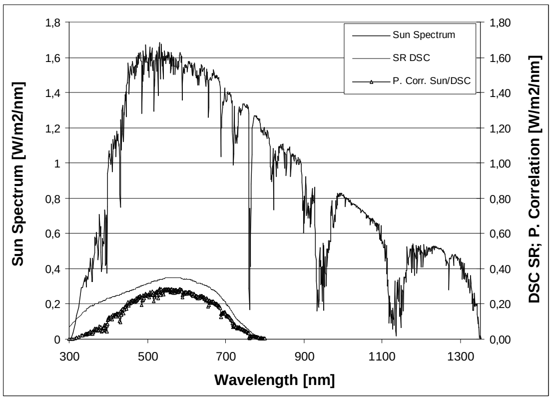

Figure 7: The sun's spectrum at sea level, the spectral response (SR) of a Dye Sensitized (DSC) PV cell and the power correlation between the Sun spectrum and a DSC PV cell. [1].

Comparison between the areas under the power correlations of the two PV cell types in Figure 6 and 7 reveals that: the crystalline silicon cell has a better spectral matching with sunlight than the DSC cell. So this Figure of Matching algorithm can be used for a quick qualitative and quantitative comparison. In a particular case if the light source spectrum is normalized in accordance to 'Standard Test Conditions' the outcome predict the PV cell efficiency under irradiance of various light sources as can be seen in Table I.

For wind energy (WE) systems, the Figure of Matching is used in optimizing the matching between the wind speed distribution spectrum at the location under investigation (S_p) and the speed Step Response (R_{Step-p}) of the electrical power generator (element p) as function of wind speed as in the matching interface MI:2.1. The conversion of rotational angular speed of the electro generator in the turbine to wind speed is done by taking into account the effective available wind power input limit in accordance to Betz' law.

For the available wind energy, the Weibull wind speed distribution is taken at Texel [5] an island in the north of the Netherlands which has also a large amount of photovoltaic panels in use and has the ambition to become energy self sufficient with renewable energy.

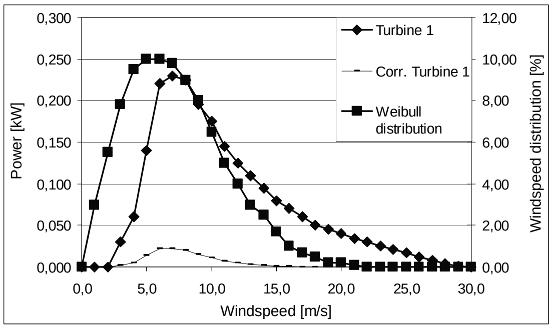

Figure 8: The Weibull wind speed distribution at the island of Texel, the wind speed converted generator response of Turbine 1 and the power correlation between wind speed distribution and turbine performance.

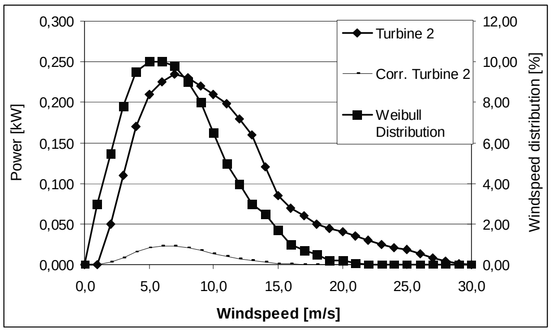

Figure 9: The Weibull wind speed distribution at the island of Texel, the wind speed converted generator response of Turbine 2 and the power correlation between wind speed distribution and turbine performance.

To enable a clearer comparison between the power correlations of Turbine 1 and Turbine 2, the two are presented again in Figure 10.

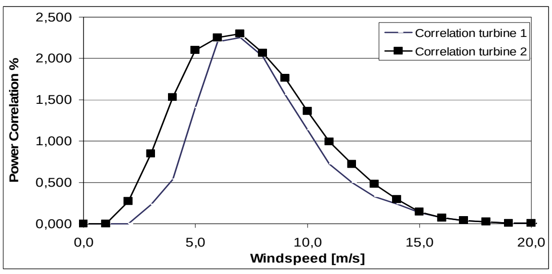

Figure 10: Comparison between the power correlation of Turbine 1 and 2.

Comparison between the areas under the power correlations of the two wind turbine types in Figure 10 reveals that Turbine 2 has a better wind speed distribution matching than Turbine 1.
So the Figure of Matching Algorithm can here be used for a quick qualitative and quantitative comparison.
The power correlation will present a figure how well the speed response of a turbine is matched with the available

wind speed distribution. Although the rotational speed of the turbine can be adjusted with a gearbox, the less adaptation is necessary the less energy loss will be suffered by the system. Therefore the initial matching of the wind speed distribution to the optimal rotational speed of the turbine is essential.

5.3 Integration Matching Interface IMI:a and IMI:b between the energy sources, carriers and converters of the two energy chains

In matching the two energy chains it is in first instance important that there will be no degradation in performance due to the integration or combination. This means that the wind turbine should be placed in such a way that it casts no shadows on the PV cells and on the other side the PV cell shall not hamper the wind towards the turbine. Configurations can be envisaged in which the PV panels act as wind funneling screens guiding the wind towards the wind turbines.

Another aspect is the availability of the energy carrier over a period of time.

Sunlight will be abundant available during the summer months but will be significantly less during the winter months as is presented in Figure 11.

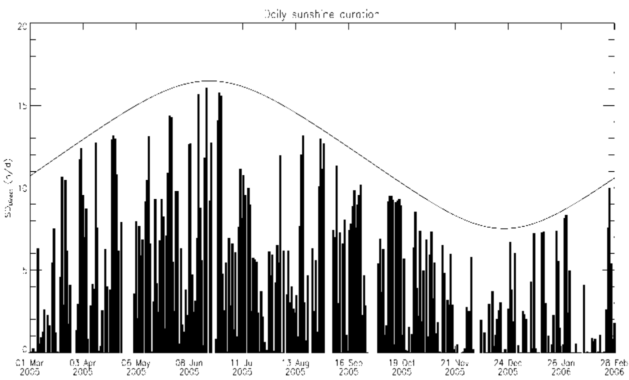

Figure 11: Daily sunshine duration (h) according to the direct method (bars) and the maximum possible sunshine duration (solid line) in one year [9]

Wind however will be more abundant during winter, spring and autumn then in summer as can be seen in Figure 12.

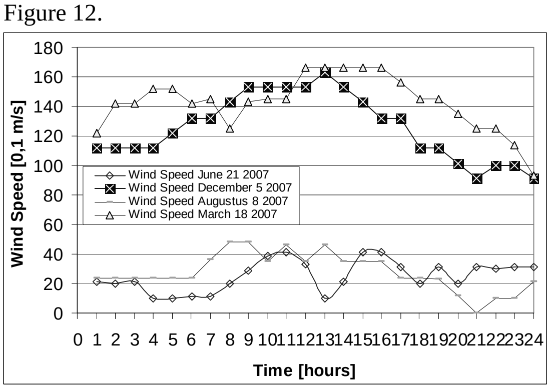

Figure 12: Seasonal variations in wind speed during one year, measured at the northern provinces of the Netherlands [9].

Combining photovoltaics and wind energy will yield a more continuous power generation over the seasons in one year.

5.4 The energy converter - storage matching (MI: 1.2 and MI: 2.2) and the integration of the energy storage of the two energy chains

Each energy chain could have its own energy storage medium. Sometimes the combined use of an energy storage medium would yield efficiency improvement and therefore a better overall matching. From practical point of view wind energy can be stored in more media than just the common batteries and capacitors as is in use for photovoltaic energy. For instance for wind energy beside water storage also storage in inertial flywheels will be an option.

5.5 The energy storage – application matching (MI: 1.3 and MI: 2.3) and integration between the application of the two energy chains

The application of the energy harnessed by the two energy chains will be the same. What will be more efficient however to have one application be run from two different energy storage media or just one combined storage system?

The answer will depend on the application.

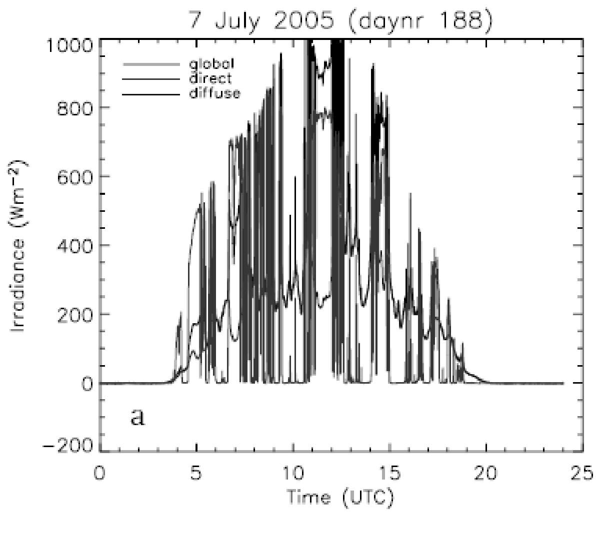

Figure 13: Measurements of sunlight at de Bilt in the Netherlands (in W/m^2) of direct normal, diffuse and global irradiance as function of time during one day on 7th of July 2005 [9].

Due to the obvious reason photovoltaics powered by sunlight will not have a contribution at night. Figure 12 demonstrates however that wind energy will also have a larger contribution during daytime than during the night. Comparing Figure 12 and 13 yields that wind energy is not really a complementary energy source for photovoltaics with regard to energy production during the 24 hours of one day.

6. FUTURE PROJECTS

As one of the future projects, the extended matching model and Figure of Matching Algorithm of combined energy systems will be applied to compare a number of energy related grand proposals that have been forwarded to the Frisian Province government with respect to the future of the Afsluitdijk (2010-2060). Amongst others, a PV solar Afsluitdijk wall, an artificial energy producing lake, wind energy parks and a Blue Energy plant (making use of the potential difference between salt and sweet water) have been envisaged as future options for the future Afsluitdijk area. It is the expectation that the new matching model and Figure of Matching Algorithm is capable of delivering more accurate power system estimations vis-à-vis standard power calculations for an integral future energy system around the Afsluitdijk, avoiding the usual over dimensioned designs and thereby optimizing costs-benefits for the Province and the investing stakeholders.

7. CONCLUSIONS

- Photovoltaics and wind energy yield together a good complementary and continuous renewable energy combination in which the lesser output of photovoltaics during the winter months is compensated by the surplus wind energy.
- A Generic Energy Matching Model and associated Figure of Matching Algorithm have been presented for combined renewable energy systems of different origin.
- The Figure of Matching algorithm can be used to probe how optimal the matching between the elements in the individual energy chains has been achieved.

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9. ACKNOWLEDGMENTS

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