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SCIENCES AND TECHNIQUES FACULTY**

**MASTER
"Energetic Systems & Renewable Energies"**

**DEVELOPMENT OF A SOLAR WASHING MACHINE FOR
RURAL APPLICATION IN DEVELOPING COUNTRIES**

Master thesis written by :

Denis PAUDECERF

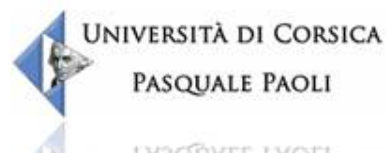
Supervised by :

Prof. Dr. HENSEL

Realised at :

Agrartechnik, University of Kassel, Witzenhausen, Germany

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INTRODUCTION

Today the energy for the human needs is mainly produced from fossil primary materials (oil, coal) that the Earth had accumulated during millions of years. Doing it, we are going to emit a huge amount of carbon dioxide in the air. This CO₂ in atmosphere acts like a greenhouse and block the warmth of the Earth. The predictions have differing views on the seriousness of the current situation but all of them are unanimous in telling that fossil energies have to be reduced or else climates will change and environmental disasters will suddenly increase.

The first people who suffer from this climate change live in the developing countries. The dryer and dryer climate is causing a shortage of water in these countries. For this reason, the agriculture is not sufficient to feed the whole population. So many people are victims of malnutrition and are exposed to several illnesses. Because of their modest means, the hospitals of these countries are not hygienic and the diseases spread from one people to another.

With this study, we want to help to reduce this hygienic problem in the hospitals of developing countries. Today, African nurses use to wash the dirty linen in the next river. In addition to the problem of the river pollution, cold water does not disinfect the clothes : water has to be warmed up. Moreover, hand washing is a hard labor done by nurses, who have a more important work to do.

In order to wash and disinfect the dirty linen in the hospitals in developing countries, without increasing the effects of the problems mentioned above, we will develop a high temperature automatic washing machine using only “clean” energy. The waste water must be recycled. This machine must produce its electrical needs because some places are not connected to the national grid. And finally the technology must be as easy as possible to obtain a long life duration with a little maintenance.

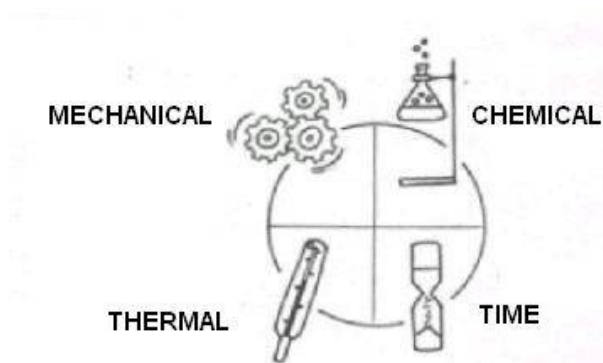
In a first part of this thesis, we will make the state of the art of washing and disinfection techniques and of existing washing machine. Then we will explain how to design the machine and why we choose these elements. Then we will speak about the experiments performed on the machine. Then we will do an ecological and an economical assessment of the project. Lastly, we will show the perspectives of the project in order to create a place where the solar washing machine can be used everyday.

I. STATE OF THE ART

I.1. Cleaning and disinfection

Cleaning means erasing every visible or invisible waste from a surface. This cleaning surface is qualified as clean. Disinfection is an operation with an instantaneous result. It erases or kills undesirable microbes. The disinfected surface is qualified as healthy and hygienic.

The effectiveness of cleaning and disinfection is well illustrated by the Sinner's circle. It shows four actions, which interact together and have an influence on the final result. If one of the actions is reduced, at least one of the others have to be increased to make up for the loss.



Sinner's circle

- **Chemical action**

It is the action of a detergent or an alkaline solution, in our case the washing product. This action is increased or reduced by the quantity of product used during the washing. The action range of this parameter is small because an over-dosed or under-dosed mix has undesirable consequences.

- **Mechanical action**

This action is brought by the use of an equipment. We informally call it “elbow oil” when it is given by a person. In the case of the washing machine, the clothes are mixed by the rotation of the drum. They rub themselves and with the drum walls. This action is increased or reduced by the duration of drum rotation. Warning, too much mechanical action can damage the delicate linen.

- **Thermal action**

Water temperature acts on the chemical properties of the product. Warm water improves various powers (soaking, confining) of the detergent. Warning again, a too hot water can harm some materials. However, the water must be warmed to about 80°C to obtain a perfect disinfection of strong texture clothes.

- **Time action**

During cleaning operation, the time action is combined with chemical action. The longer the product acts on the clothes, the higher the cleaning power is. For a washing machine, this parameter is easily adjustable and without risks.

1.2. Historical

Our ancestry would be relieved if they knew what the washing machine is. Formerly, the hard labor of hand washing was twice or three times a year and was during several days. In the middle of the 19th century, the first wash boiler appears. Water is warmed by burning wood, so the soaking time is highly reduced.

The first real innovation is patented by Mr Hénin the 26th April 1904. This invention is a vertical wood vessel which has a double bottom and walls with relief. A shaker is cranked, this movement gives the clothes a rub instead of hand-scrubbing. Progressively, wood is replaced by iron or copper vessel in order to warm water with biomass energy. Water is manually removed from clothes with a mangle, a machine which press the clothes between two rollers.

The first electric machine appears in the 20's. Then, in 1932, Alfred Conord invents a machine which washes and wrings out in the same place. The clothes are put in a drum, which turns very fast and uses the centrifugal force to extract water. We now speak about spinning.

Half-automatic programs appear, the user must select which cycle (washing, soaking, spinning) have to be run.

In the 50's, the washing machine become more popular, several technologies appear, in particular the horizontal axis drum, which mix the linen using only the gravitation. En 1957, Vedette create the first automatic control unit and makes the automatic washing machine a new fashion. They represent 45% of the market in 1966, 47% for the half-automatic, and only 8% for the manual.

In the 80's and 90's, the electronic replaces the mechanical automatic control unit. Machines are more and more sophisticated. Sometimes they have got dozens of programs depending on material, white or color, temperature... Several sensors control water level, spinning speed, drum rotation duration... They consume less and less water and improve the washing quality.

1.3. Choice of a type of machine

Knowing the historical of washing machine, we can now choose which type of machine is better for our project.

The vertical axis drums are mostly sold in Asia and so they are not very present in the other continents. Moreover, they consume more water in average because the whole linen must be submerged. So we choose a horizontal axis machine because they are easier to find are they consume less water.

This type of machine exists with top or front load. This parameter is not very important but we will choose a front load machine because it is possible to observe what is happening in the drum during the cycles.

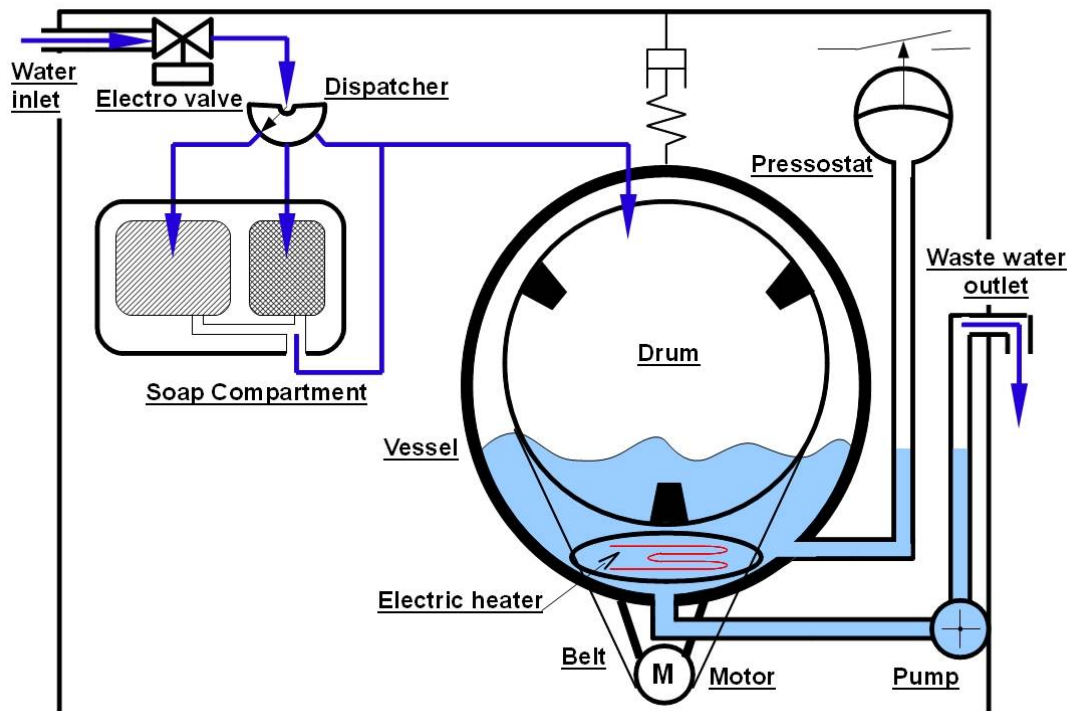
We choose an automatic machine to let the user free during the whole duration of the washing. It is better to choose a mechanical automatic control unit because they have a technology which is easier to modify. They are certainly more present than the electronic ones in developing countries.

To summarize, the type of machine that interest us in this study is a front load horizontal axis washing machine with a mechanical automatic control unit.

I.4. Washing machine working

The type of washing machine described above is composed of these elements :

- A **solenoid valve** : it controls the water inlet, it is closed when not powered.
- A **soap compartment** : it often is composed of a few compartments (pre-washing, washing, softener...), where the water goes or not, depending on the dispatcher position.
- A **watertight vessel** : a block of concrete is fixed on it as a ballast. It is connected to the frame through a spring-damper system. Inside the vessel are the drum and the electric heater. Water comes from the top and exits through the bottom.
- A **drum** : it is a cylinder in rotation where the user places the linen, the walls have relief in order to properly mix the clothes.
- A **pressostat** : its air inlet is connected to a vertical tube going to the bottom of the vessel. Depending on the water level, it acts on electric switches and so controls other elements.
- An **electric heater** : it is placed on the bottom of the vessel in order to warm up the water. Temperature is controlled by a thermostat.
- A **motor** : it is fixed to the vessel and makes the drum turns with a belt.
- A **pump** : it evacuates water from the vessel to the outlet. Before it, there often is a dirt filter. There is no valve to block the water from the vessel, so the waste water outlet must be placed on a higher level than the water in the vessel.
- An **automatic control unit** : it is an electronic circuit, which controls the electricity supply to the elements of the machine. A timer connected to a step-by-step motor makes a selector turns. This one opens or closes several switches thanks to notched wheels.



Working schema of a washing machine

1.5. Washing programs

A washing machine executes a washing program, it controls all elements of the machine depending on the time.

A washing program is made of a few cycles :

- **Washing cycle**

The solenoid valve opens, the dispatcher aims the water at one of the soap compartments. The vessel fills up until the pressostat switch off the valve. The electric heater warms up the water. The motor alternates between rotation times and break times. The drum spins at about 50r/min and changes direction every time (clockwise and then anticlockwise). The washing rhythm depends on linen type. Weak cloth can be damaged if the rotation times are too long.

Cloth	Rotation times	Break times
Strong	10 to 15s	3 to 5s
Delicate	3 to 5s	10 to 15s
Very delicate	1 to 3s	About 1min

This cycle can be more than one hour long for a washing load of about 5kg. Some programs include sometimes a pre-washing, which is similar to the washing.

Water is warmed up only for the washing (and pre-washing if exists). At the end of this cycle, the pump turns on in order to empty the vessel.

- **Soaking cycle**

Soaking cycle is nearly similar to washing cycle. The only differences are that the dispatcher aims the water right at the vessel and that this water is not warmed up.

Motor alternates still rotation and break times. We speak now about soaking rhythm.

The soaking cycle duration is about 5 minutes.

- **Spinning cycle**

Spinning is performed by drum rotation, only in one direction. The speed often increase step by step. Depending on machines, the maximum speed is between 600 and 1600r/min.

The spinning cycle duration is about 5 minutes.

Depending on the strength of the linen, the programs make from 3 to 5 soaking-spinning cycles. It is during these cycles that the machine consumes the more water (only cold).

1.6. Ecological washing machine ?

There is today no completely ecological washing machine, consuming no primary energy and recycling its waste water.

More and more, it appears machines with two water inlets in order to use solar domestic hot water for example. But these machines still consume public electricity which is not 100% clean. They also pollute a significant quantity of water which is not always aimed at a water purifier.

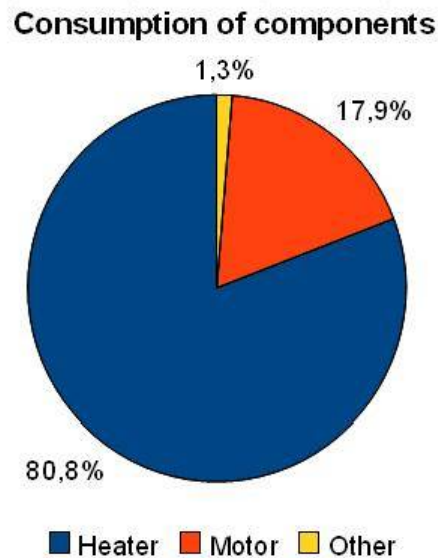
II. CHOICES AND DESIGN

II.1. Machine consumption and choice of a type of energy

We measure the power and the electrical consumption of the machine for a “normal” program (60°C, 5kg load, no pre-washing). We use a power counter. Depending on the modes, this device can measure the instantaneous power $P(t)$ or the total energy consumed W_{tot} during the duration T of the record. We notice that the total energy consumed can be verified by the following calculation :

$$W_{tot} = \int_0^T P(t) \cdot dt$$

Looking which elements are turned on at the the instant t , we can identify the power of every element of the machine. Knowing how long each element is turned on, we can show the consumption of every component.



Electrical consumption (60°C, 5kg load, without pre-washing)

We can see that more than 80% of the energy is consumed by the electric heater. If we warm up water with an other type of energy, the electrical consumption of the machine would only come from the motor and the other elements (solenoid valve, pump, electronic components). So it would be about 19% of the present consumption.

Water consumption is also measured. About 12 liters of water go in the machine at every filling. The program makes one washing cycle with hot water and three soaking cycles with cold water.

Electrical consumption		Water consumption	
Total	Without heater	Hot	Cold
1300 Wh	250 Wh	12 L	36 L

Total consumption of electricity and water

When we think about integrating renewable energies in developing countries, solar energy is the first idea which comes. This plentiful and inexhaustible energy can give directly warmth and indirectly electricity with the photovoltaic technology. If we base on the consumption measurement made above, an easy calculation shows that we don't need a huge surface of solar panels to supply a washing machine with electricity and hot water.

Depending on different references, the average of solar energy in Witzzenhausen is from 870 to 925 kWh/m²/year. So it is about 2,4 kWh per day. The photovoltaic efficiency is more than 10%, so one square meter of panels would be enough to supply 250 Wh, the electrical need for one washing per day. The energy necessary to warm up water in the program is about 1 kWh. It was supplied by an electric heater which have an efficiency of about 100%. A solar heater has an efficiency from 60% to 80%. Worst of all, it needs 1,6 kWh (so a surface of 0,66m²) in order to warm up water to 60°C once a day.

So, if in Witzzenhausen less than 2m² of solar devices is enough to wash a 5kg load everyday, the same system in developing countries would not need a huge expensive solar installation.

II.2. Choice and design of solar thermal system

II.2.1. Choice of technology

A solar thermal system uses solar energy in order to warm up a fluid, water in our case. Solar collectors with storage tanks is a technology that is often used for the household water heaters. Mostly, the collectors are laid on the roof of the houses. A frost-resistant liquid transmits the warmth from the collectors to the storage tank through a heat exchanger. A pump, which is controlled by an electronic regulation system, makes the liquid flows. Such installation seems to be excessive for a washing machine. Other easier systems exist and would make the technology more adapted to the developing countries.

For example, we do not need to use a frost-resistant fluid in countries where the yearly minimum temperature is about 5°C. We can eliminate the heat exchanger. The same water will flow between collector and tank, waiting to be used by the washing machine.

To simplify the system again, we can use a thermosiphon. This technology makes the fluid flows by natural convection. The flow rate is automatically regulated, no pump and no electronic regulation system are necessary. We notice that the most frequent failures of solar water heaters come from the pump or its regulation. The system would be more reliable without it.

The only drawback of the thermosiphon is that the tank must be on a higher level than collectors. In this way, the water inside the collector is warmed up by the sun. Having a lower density than the cold water located in the inlet of the collector, it will naturally flow over. When this water arrives in the tank, it expels colder water, which causes a hydrodriving pressure, which makes the liquid flows in a natural convection loop between the collector and the tank.

II.2.2. Choice of collector

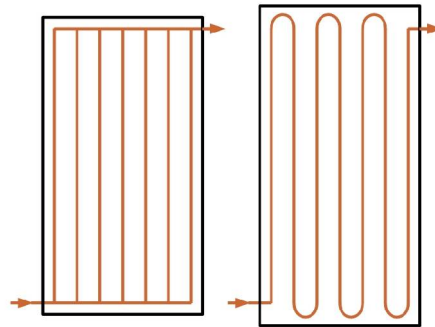
It exists different types of collectors, all of them are not adapted to a thermosiphon system. Indeed, the fluid must always flow over from the inlet to the outlet of the collector. It must have the least possible disruptions in the tubes in order to have the least pressure losses.

We usually sort the solar collectors into two families : the flat collectors and the vacuum tubes collectors.

Flat collectors are made from one or more sheets, absorbing solar radiation. Then the liquid absorbs this warmth because it flows in tubes which are linked to the sheets. This assembly is placed behind

a glass sheet in a watertight and isolated box. These collectors can be self-constructed. Vacuum tubes collectors are vacuum glass tubes in which are placed metal tubes filled with a fluid which absorb the solar radiation. They are more efficient than flat collector because they lose less warmth. But they are more expensive and can not be self-constructed. Moreover, the tubes have often very small diameter and create high pressure losses.

We will choose a flat collector with a ladder network of tubes.



Flat collectors : ladder network (left) and snake network (right)

II.2.3. Tank design

The tank must fulfill the following functions :

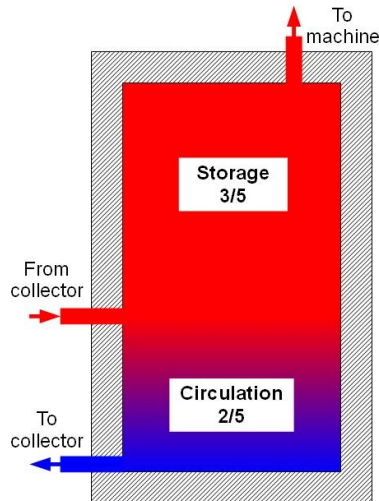
- To store a volume of hot water which is equivalent to the daily need of the washing machine
- To let the thermosiphon flow circulates
- To have a good thermal insulation ($U < 1 \text{ W/m}^2/\text{K}$)

Hot water must be drawn on the higher level of the tank, there is the higher water temperature. The tank needs also an inlet and an outlet to close the thermosiphon loop. The outlet is connected to the collector inlet and must carry the coldest water of the tank. So the outlet must be on the bottom of the tank. The water warmed up by the collector arrives through the inlet of the collector. It is stored on the top of the tank. The level of the inlet establishes the limit between the two parts of the tank, one for the storage (higher), the other for the flow (lower). The volume of the storage part must be equal or higher than the daily hot water need of the machine.

The global heat transfer coefficient U [$\text{W/m}^2/\text{K}$] depends on the thickness e [m] and the thermal conductivity λ [W/m/K] of the material insulating the walls. Here is the calculation for 5cm of glass wool.

$$U = \frac{\lambda}{e} = \frac{0.04}{0.05} = 0.8$$

We have a good insulation if the global heat transfer coefficient is lower than 1.



Schema of the tank

In our case the machine has a 12L hot water consumption. We want that our prototype can realize one washing per day. This daily quantity of water must be equivalent to the $\frac{3}{5}$ th of the total volume. So we need minimum a 20L tank.

For our prototype, we have a 30L tank, so 18L storage volume.

II.2.4. Mixing system

We want to design the system to get a maximum temperature of about 80°C. But we must add a mixing system in order to wash with lower temperature. This mixing system must :

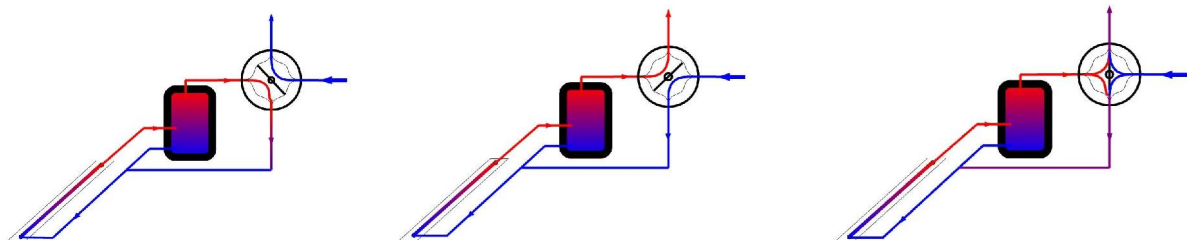
- mix cold water and solar hot water
- supply the machine with cold water for the soaking cycles
- reload the tank at the same time when water is drawn to the machine

We can fulfill these two obligations using a 4-ways valve. The schema below shows three configurations of the valve :

a. cold water is available for machine, thermosiphon flows.

b. hot water is available for machine, thermosiphon is reloaded with new cold water

c. mixed warmed water is available for machine, thermosiphon is reloaded with warm water



a.

b.

c.

Schema of the thermosiphon with the 4-ways valve mixing system

This system of thermosiphon with a 4-ways valve is the real innovation of this project. If the cold water comes from a tank which is open to the atmospheric pressure, we have a system which draws water with adjustable temperature. This system can be self-constructed, doesn't need electricity and is without overpressure risk. So, it is totally adapted to the remote areas in developing countries.

It is also possible to connect the system to the water national network. In this case, an expansion tank must be added.

If the cold water comes from a tank, the expansion volume due to the warming of water goes to the cold water tank.

II.2.5. Collector surface calculation

The collector surface S is the parameter which is the more difficult to estimate because it depends on many variables : slope, direction and type of collector, solar beam and diffuse radiation, ambient temperature, cold water temperature, hot water needs.

However, we can approximate this constant knowing the following information :

- The number of washing per day n
- The quantity of hot water for one washing V in liters
- The maximum temperature necessary for the washings T_{max}
- The mean cold water temperature T_{min}
- The daily mean radiation of the place Ed in Wh/m²/day on a horizontal surface and during the period of use.

$$S = \frac{C n V (T_{max} - T_{min})}{K_i Ed}$$

The coefficient C includes the specific heat and the density of water, and a constant named the daily mean efficiency of the system. This last value is experimentally figured out further in the thesis and can be used for every system using about the same materials than our prototype.

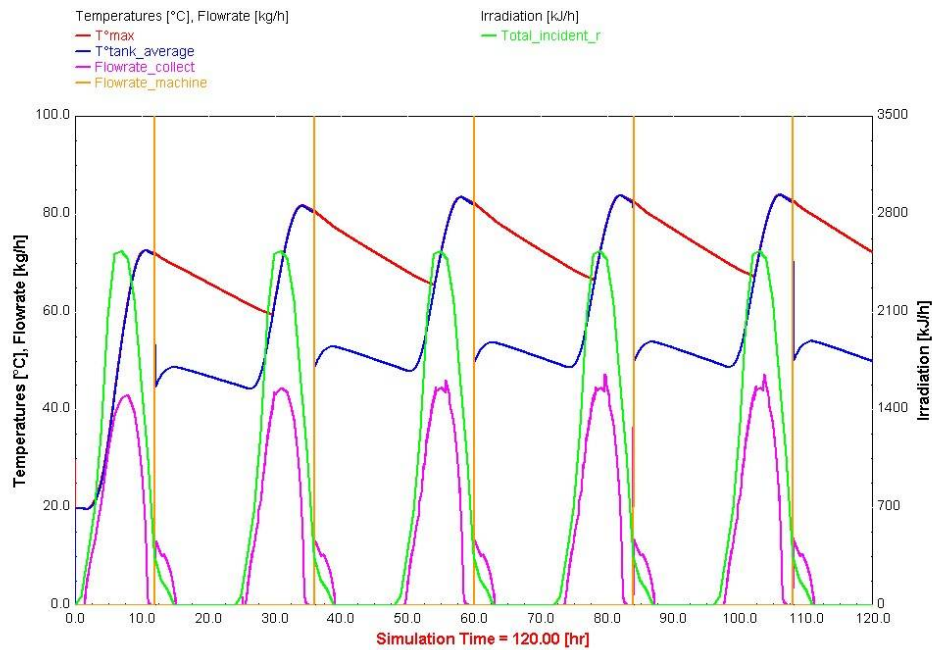
This calculation is true for a not shady and horizontal collector. Correction coefficients K_i related to the place must be added in order to consider the shadow, the slope and the direction of the collector.

The collector surface is an important parameter but does not need a high precision mostly when using a self-regulated thermosiphon system. More important is to be sure that the water temperature will never reach 100°C. To design the prototype, we use TRNSYS, a dynamic simulation software applied to renewable energies or multi-zones buildings.

In this software is a calculation module specific about thermosiphon systems. We set the parameters of collector, tank and tubes. The inputs indicate the ambient temperatures, solar irradiance and the flow rates of hot water consumed depending on the time. So, the software calculates temperatures and flow rates in several points of the system.

The following graphs show the temperature on the top of the tank (red curve), the mean temperature of the tank (blue curve) and the flow rate on the inlet of the collector (purple curve). The solar irradiance (green curve) represents two profiles of a day, either sunny or cloudy. The yellow vertical bars indicate the instant when water is drawn to the machine. To simulate extreme conditions, the hot water is not mixed. We draw water at the maximum temperature of the system.

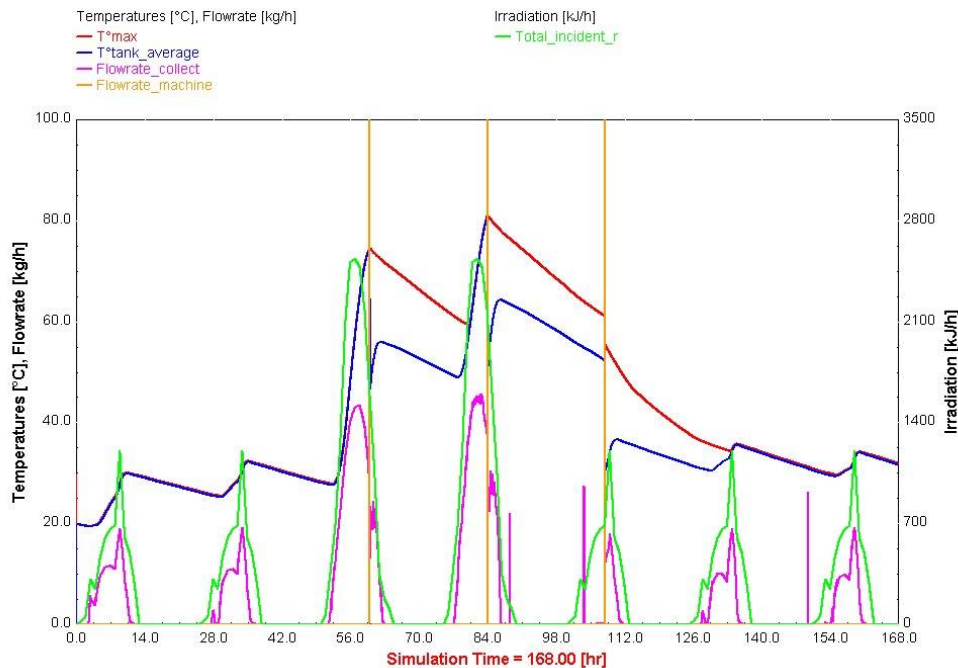
The first simulation shows five days in summer with a use of one washing every day at 6pm.



TRNSYS simulation : summer, one washing per day

Except the first day, water has a temperature of about 80°C at the end of the day. After drawing water, the temperature on the top of the tank is still 80°C while the mean temperature of tank drops to about 45°C. The next day around noon, the blue and the red curves are joined again, it means that the tank temperature is uniform again.

This simulation shows that the prototype can wash at 80°C every sunny day. What about cloudy days?

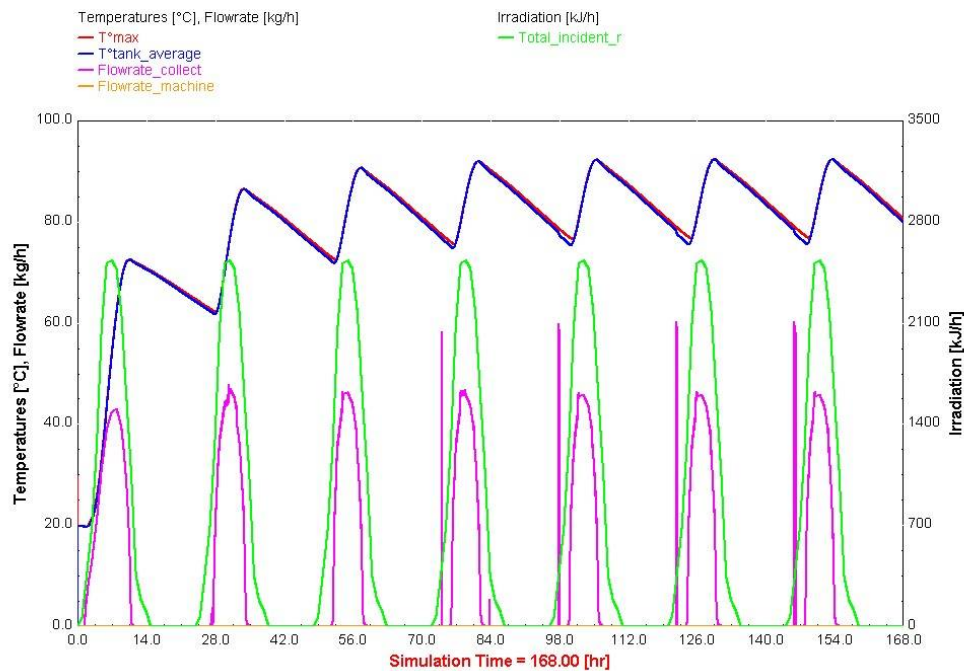


TRNSYS simulation : spring, cloudy week with two sunny days

When days are cloudy with sunny spells (days 1, 2, 5, 6 and 7), water is warmed up to about 35°C. This temperature is enough to wash domestic linen but not enough to disinfect hospital clothes. Days 3 and 4 are sunny, the water temperature reaches a maximum of 75°C, then 80°C at the end of the days 3 and 4. If we know that the next days are cloudy, it makes sense to use the available hot water as early as possible. In the simulation, the next washing is made at the end of the day 5 with a temperature of 55°C, it would be 70°C during the night between the days 4 and 5.

This simulation shows that the prototype can also be used during spring or autumn. Its use is less regular and depends more on the weather. These statements are senseless in developing countries where the climate does not change a lot but stays very sunny.

We must now check if an over-warming problem can exist if the machine is not used during a long period.



TRNSYS simulation : summer, one week without use

Thermosiphon has the benefit of self-regulation. In this way, the temperature of the system never exceeds 90°C. So there is no risk that the water boils and destroys anything in the system.

The dynamic simulation of the thermosiphon gives us the possibility to adjust the collector surface depending on the weather of the place. The reliability of this calculation must be proved after comparing experimental results and simulation results.

II.3. Electric and electronic design

II.3.1. Inconsistency

Photovoltaic panels supply direct current with 12V voltage. But, all the electric devices in the existing machine work with alternating current with 230V voltage. There are two possibilities to solve this inconsistency :

1. To use an inverter

It is possible to connect an inverter 12V DC / 230V AC between the photovoltaic panels and the washing machine. We don't change anything of the technology inside the machine. It will consume a little bit more electricity than before due to the inverter consumption, which has an efficiency of about 90%.

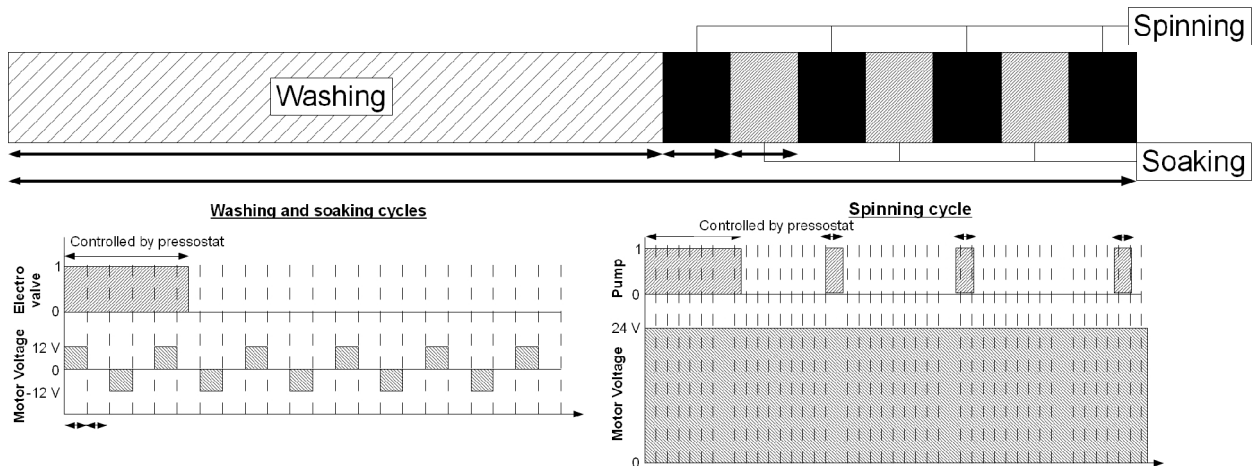
2. To replace the alternating current by direct current electric devices

It is also possible to use direct current motor, pump and solenoid valve in the machine. With this solution, the automatic control unit must also be changed because it was designed for 230V AC devices. So, we can develop a new automatic control unit with easier technology. New programs can be created with the aim of reducing the consumption of water and electricity.

The second solution respects more the objectives of the project : easy technology and consumption reduction.

II.3.2. Washing programs simplification

The solar washing machine must adapt itself to a need, and must have an easy use. For this first prototype, we will choose an unique program which washes efficiently.



Solar washing program

This unique program has one washing cycle, one first spinning cycle, and then few soaking and spinning cycles. The speed of the DC motor is simply controlled by its voltage ($\pm 12V$ for washing and soaking, $24V$ for spinning).

We keep a washing and soaking rhythm alternating rotation times (in the two directions) and break times. Solenoid valve is still controlled by the pressostat. To save energy, the pump is also controlled by the pressostat and is switched off when the vessel is empty.

II.3.3. Electronic card

Modern washing machines have electronic automatic control unit using a microcontroller. This technology using data-processing has the benefit of controlling the mechanical devices with very high precision and can manage information from many sensors. The drawbacks of this technology are the reliability and the very expensive repair because it can be realized only by the manufacturer, which often advises to replace the whole machine. So, this technology is not adapted to an use in

remote areas in developing countries.

We prefer electronics components which are cheap and easily replaceable for a better reliability and an easy maintenance. These components are :

- **Electromechanical relays**

A relay is a commanded switch. In its easier configuration, it has 5 pins : two for the solenoid command, and three for the switch. We also use one relay with one solenoid controlling two switches (8 pins).

- **Timer NE555**

The component NE555 has several applications as a timer. Time is set by external resistances and capacitors. So this duration is independent from the voltage of the circuit. We use this component in two different configurations :

The monostable operation : the pins 6 and 7 are linked together. From this node is connected a resistance R to the + and a capacitor C to the -. When the trigger of the component (pin 2) detects a falling edge, the outlet signal (pin 3, initially at 0) switches to 1 during the time t_{mono} , calculated in seconds.

$$t_{mono} = 1.1RC$$

The astable operation : the pins 2 and 6 are linked together. From this node is placed a capacitor C to the - and a resistance R_2 to the pin 7. We connect an other resistance R_1 between the pin 7 and the +. While the timer is powered, the outlet signal alternates between 1 and 0. The durations t_1 and t_0 of respectively 1 and 0 level are each adjustable.

$$t_1 = 0.693(R_1 + R_2)C$$

$$t_0 = 0.693R_2C$$

- **D flip-flop**

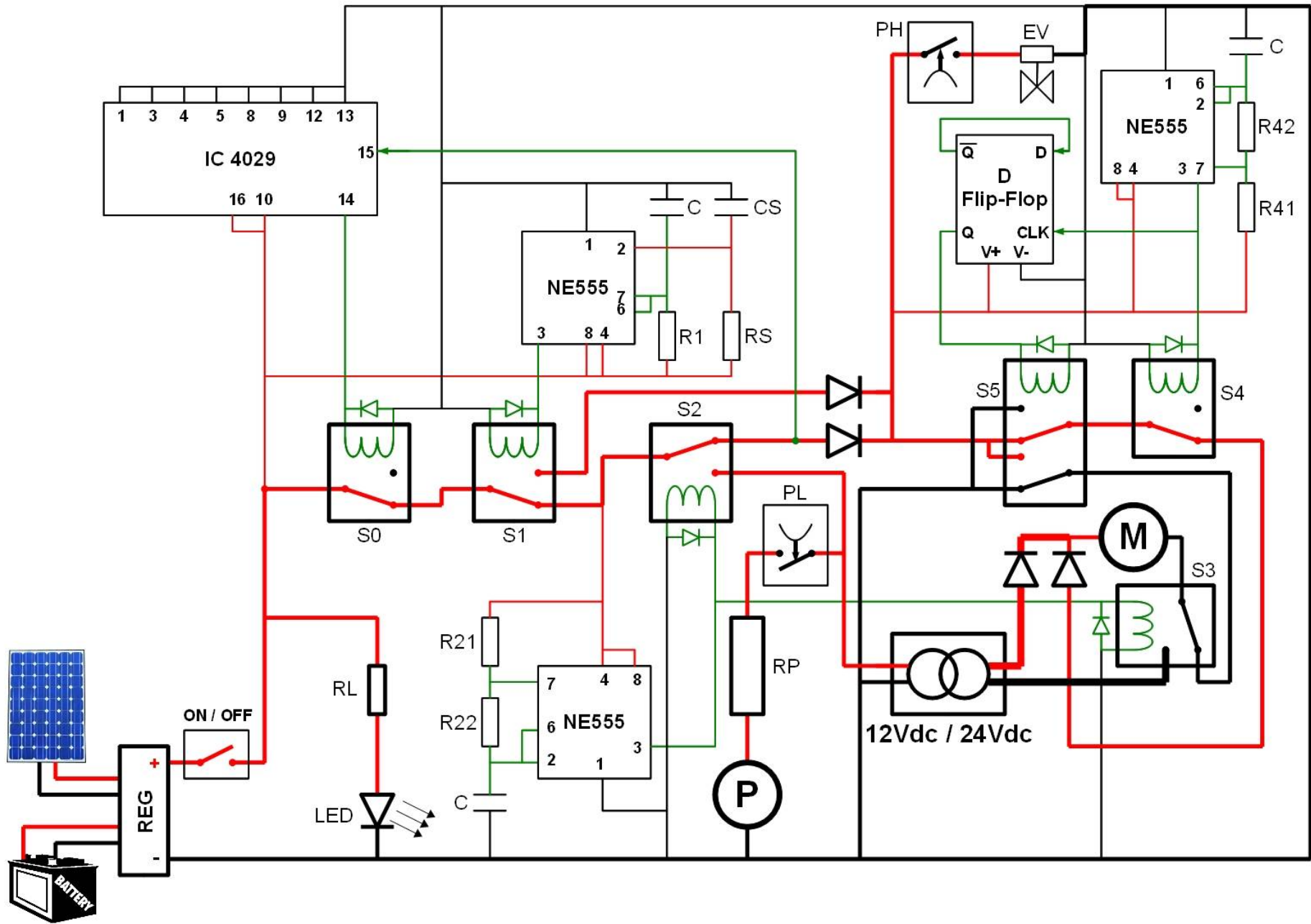
The flip-flop is the basic element of the sequential logic. The D flip-flop has two inlets and two outlets which can be at logical levels 0 or 1. The two outlets always are at opposite levels and are named Q and \bar{Q} . In most applications, an inlet named CLK (clock) is supplied by an alternating edge signal and the other inlet named D controls the level of the outlets. Linking the outlet \bar{Q} to the inlet D , the outlet Q supplies an alternating edge signal which doubles the period of the CLK signal.

- **4 bits counter IC4029**

A n bits counter is an assembly of n D flip-flops. The level (0 or 1) of the n outlets is a binary number which indicates the number of rising edges counted on the inlet CLK since the counter is supplied with electricity.

- **Power transformer 12V/24V**

This box transforms a direct voltage 12V in a direct voltage 24V.



Schema of the electronic card of the solar washing machine

On the schema, the power circuit is drawn in bold and the command circuit is drawn with thin lines. The 24V supply is drawn with very thick lines. Red lines are connected to the +, black lines to the ground. Green lines represents the command wires. Every relay is represented in “0” position, as if the solenoid is not powered.

Diodes of the command circuit protect the solenoids of the relays, standard diodes *IN4007* are enough. But the diodes of the power circuit must block the high current going to the pump and the motor. They must block a current which is depending on the mass of wet clothes in the machine. We need to go further into the design of the diodes of the power circuit because a wrong design makes the diodes burn.

The photovoltaic panel and the battery are connected to a charge regulator. The role of this device is to control the charge level of the battery and to act on the direction of the photovoltaic current : either to reload the battery, or to directly supply the machine.

The manual switch *ON/OFF* can be get back from the machine. It opens or closes the current to all the elements of the machine.

The first element powered is the light-emitting diode *LED*. Its characteristics are a specific current i_{LED} and a specific voltage U_{LED} . choose $U_{LED} \leq 12V$. Then we can design the resistance R_L : its resistance value R_L in ohms and its maximum power P_{RL} in watts.

$$\boxed{R_L \geq \frac{12 - U_{LED}}{i_{LED}}}$$

$$\boxed{P_{RL} \geq R_L \cdot i_{LED}^2}$$

The counter *IC4029* is powered since the machine has been switched on, it commands the relay *S0*. When the program reaches the wanted number of soaking–spinning cycles, this relay opens. It is the end of the program, only the LED is powered until the user switches off with *ON/OFF* button. In the schema above, the counter is set in order to switch off at the end of the third soaking–spinning cycle. It is possible to change this parameter in adding other components (flip-flops). This possibility is not in this study because it complicates the system without necessity. In fact, references in washing techniques write that three cycles are enough to effectively soak the linen. Moreover, it is always possible to act on the cycle duration.

The monostable timer NE555 linked to the relay *S1* is powered since the machine has been switched on. The components *RS* and *CS* are designed in order to send a falling edge to the trigger after a very short time. The relay *S1* switches in “1” position quasi-instantaneously after having switched on the machine. It stays in this position during the washing time t_{wash} . Depending on this duration, we can choose the resistance value *RI* in ohms.

$$\boxed{R_1 = \frac{t_{wash}}{1.1C}}$$

To simplify the system, it is better to choose the same value for all the capacitors of the electronic card ($C = 1000\mu F$) and to adjust the durations with the resistances.

During the washing cycle, the solenoid valve *EV* is powered, it opens the water inlet and fills the vessel. The pressostat switches off this circuit when the water reaches the high level (pressostat switch *PH*).

A period of the washing rhythm is in four times. The motor voltage during this period must be : 0V,

then 12V, then 0V then -12V. The change from $\pm 12V$ to 0V is simply made by the relay $S4$ which is controlled by an astable timer NE555. The rotation times t_{12V} and stop times t_{0V} are set by the resistances $R41$ and $R42$.

$$R_{42} = \frac{t_{12V}}{0.693C}$$

$$R_{41} = \frac{t_{0V}}{0.693C} - R_{42}$$

We can see that the rotation time is always lower than the break time. If we want to have two equal durations, it has to be : $R_{41} \ll R_{42}$.

The inversion of poles (12V or -12V) is possible with the double relay $S5$. It has to be made twice a period. The period of the signal sent by the NE555 must be doubled. The signal of the timer is sent to the D flip-flop, which controls the double relay $S5$.

At the end of the washing cycle, the relay $S1$ switches to “0” position. It powers the astable timer NE555, which controls the relays $S2$ and $S3$. $S2$ supplies the soaking circuit (same as washing circuit) in “0” position, or the spinning circuit in “1” position. $S3$ acts on the ground of the motor : 12V for soaking and 24V for spinning. The soaking and spinning time, respectively t_{soak} and t_{spin} , are controlled by the resistance values R_{21} and R_{22} .

$$R_{22} = \frac{t_{soak}}{0.693C}$$

$$R_{21} = \frac{t_{spin}}{0.693C} - R_{22}$$

As below, spinning time is always lower than soaking time. If we want to have two equal durations, it has to be : $R_{21} \ll R_{22}$.

When spinning, the power transformer is supplied and gives a 24V voltage to the motor. The pump is supplied depending on the level of water in the vessel : the part of the pressostat PL switches off when the level is low (empty vessel). The pump voltage can be adjusted with the resistance RP . In fact, a too powerful pump is noisy and consumes a lot of energy. Reducing the voltage, the speed of rotation and the current consumed are reduced. This resistance can be designed after measuring the current i_p consumed by the pump in order to empty the full vessel, when it is supplied by a U_p voltage. So we can calculate the resistance value R_p in ohms and the maximum power P_p in watts.

$$R_p \geq \frac{12 - U_p}{i_p}$$

$$P_p \geq R_p \cdot i_p^2$$

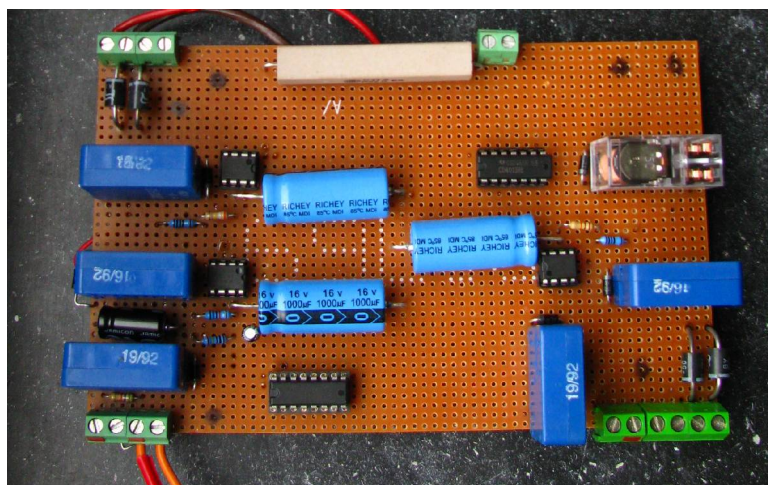
A lot of improvements can be added to this first prototype. For example a “short washing” mode can be realized in shutting the wire to the resistance RI with a switch, which supplies either RI or another resistance with a lower value.

Some 4-ways valves are motorized, the valve can be controlled depending on the temperature of the cold and hot water.

Once the user have choosen his needs for the program (washing, soaking and spinning times, washing rhythm, maximum load of wet clothes, characteristics of motor, pump and LED), he can design and assembly the specific components (resistances, capacitors, diodes).

Here is an example of the components used for the prototype built in Witzenhausen :

Integrated circuits, power transformer					
Name			Quantity		
Timer NE555			3		
Double D Flip-flop IC4013			1		
Counter IC4029			1		
Power transformer Statron 12VDC/24VDC 240W			1		
Diodes					
Use	Type	Maximum current	Quantity		
Command	1N4007	1 A	6		
Power	P1000S	10 A	4		
LED	5mm yellow, 1,6-2V	2 mA	1		
Relays					
Reference	Pins	Command voltage	Power maximum voltage	Maximum power	Quantity
S0 S1 S2 S3 S4	5	12 V	125 V	600 VA	5
S5	8	12V	60 V	400 VA	1
Electrolytic capacitors					
Reference	Capacity	Maximum voltage	Quantity		
C	1000 μ F	20 V	3		
CS	0,1 μ F	50 V	1		
Resistances					
Reference	Resistance value	Maximum power	Quantity		
RL	5,6 k Ω	0,25 W	1		
RP	0,68 Ω	11 W	1		
RS	1 M Ω	0,25 W	1		
R1	2,7 M Ω	0,25 W	1		
R21, R41	100 Ω	0,25 W	2		
R22	390 k Ω	0,25 W	1		
R42	10 k Ω	0,25 W	1		



Components list and picture of the electronic card of the prototype

II.3.4. Photovoltaic design

In order to design the photovoltaic system, we need to know the global electrical consumption E during the whole washing program. The easiest method to know this constant is to measure it when the machine works with a maximum load. It can also be approximated with a calculation if we know the current i_i and the voltage U_i of every element i (motor, pump, solenoid valve, electronic card).

$$E = \frac{1}{3600} \sum_i U_i \int i_i(t) dt$$

with E [Wh], U [V], i [A] and t [s]

For this first prototype, we suppose that the consumption of the solar washing machine is a little bit less than the conventional machine without the water heater. It was 250Wh for a “normal” program with a 5kg load.

Knowing the predicted number of washing per day n , we get the daily electrical consumption E_{el} .

$$E_{el} = n \cdot E$$

The daily mean energy available must be higher than the daily consumption. It is a function of the daily mean solar radiation Ed and the correction coefficients K_i (see the thermal collector design), the photovoltaic panel surface S and the efficiencies of the panel η_{PV} and of the system η_{sys} (charge regulator, wires, wear with time). We use a value of 0.9 for this last one.

$$E_{el} \leq K_i \cdot Ed \cdot S \cdot \eta_{sys} \cdot \eta_{PV}$$

with Ed [Wh/m²], S [m²]

The power P mentioned on the photovoltaic panel is always calculated for a 1000W/m² irradiance.

$$P = 1000 \cdot \eta_{PV} \cdot S$$

So we can estimate the photovoltaic power that we need depending on the electrical consumption, the daily mean radiation and the system efficiency.

$$P \geq \frac{1000 E_{el}}{K_i \cdot Ed \cdot \eta_{sys}}$$

with P [W], E_{el} [Wh] and Ed [Wh/m²]

Once we know this data, we can estimate the surface of the photovoltaic panels that we must install depending on their efficiency. The following mean values can be used : mono-crystalline (13%), poly-crystalline (12%), amorphous (5%).

$$S = \frac{P}{1000 \eta_{PV}}$$

The battery is used to store the photovoltaic energy and to power the machine whatever the weather. The battery stops powering when it exceeds its discharge limit L (80% for the solar batteries, 50% for the car batteries). The solar batteries are better to store solar electricity, they will have a longer life. But they are expensive for a developing country comparing to the car batteries.

The thermal study has shown that the machine can be used one or two cloudy days after the last sunny day. So we fix the number of self-running days Nd at 3 days.

We calculate the battery capacity depending on the number of self-running days, the discharge limit, the electrical consumption and the voltage of the photovoltaic system U (12V).

$$C \geq \frac{Nd.Ed}{L.U}$$

Here are the characteristics of the photovoltaic system of the prototype of Witzenhausen. These values are calculated with a need of one machine per day consuming about 200Wh and a summer daily mean radiation of 5000 Wh/m².

Poly-crystalline photovoltaic panel		Battery	
Maximum voltage	20 V	Type	Car
Power	45 W	Discharge Limit	50 %
Surface	0,38 m ²	Tension	12 V
Efficiency	11,8 %	Capacity	100 A.h

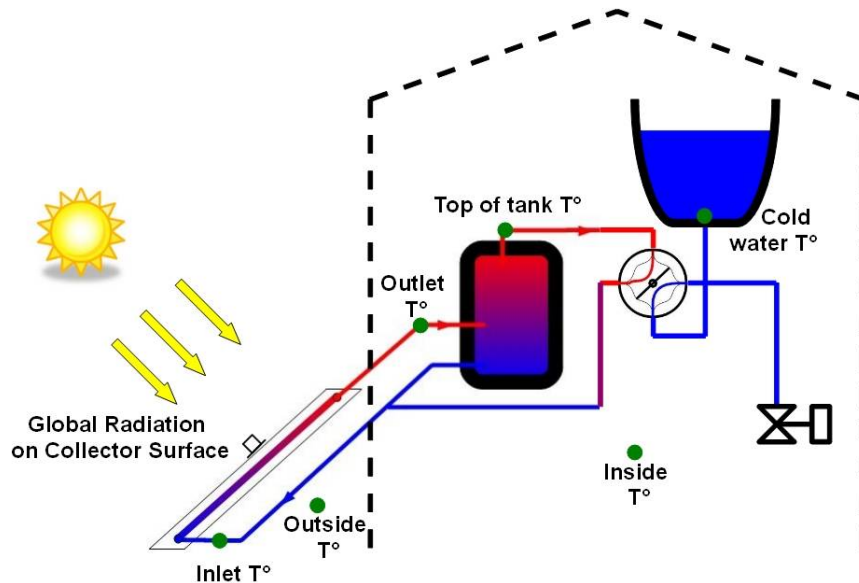
Characteristics of the photovoltaic system of the prototype

III. EXPERIMENTATION

III.1. Sensors

Our different experiences permit us to measure the efficiency of the thermal system, to figure out the values necessary for designing the system (daily mean efficiency, electrical consumption) and to validate the TRNSYS simulation.

So, we need to measure data depending on the time thanks to sensors and a database system.



Sensors on the solar washing machine

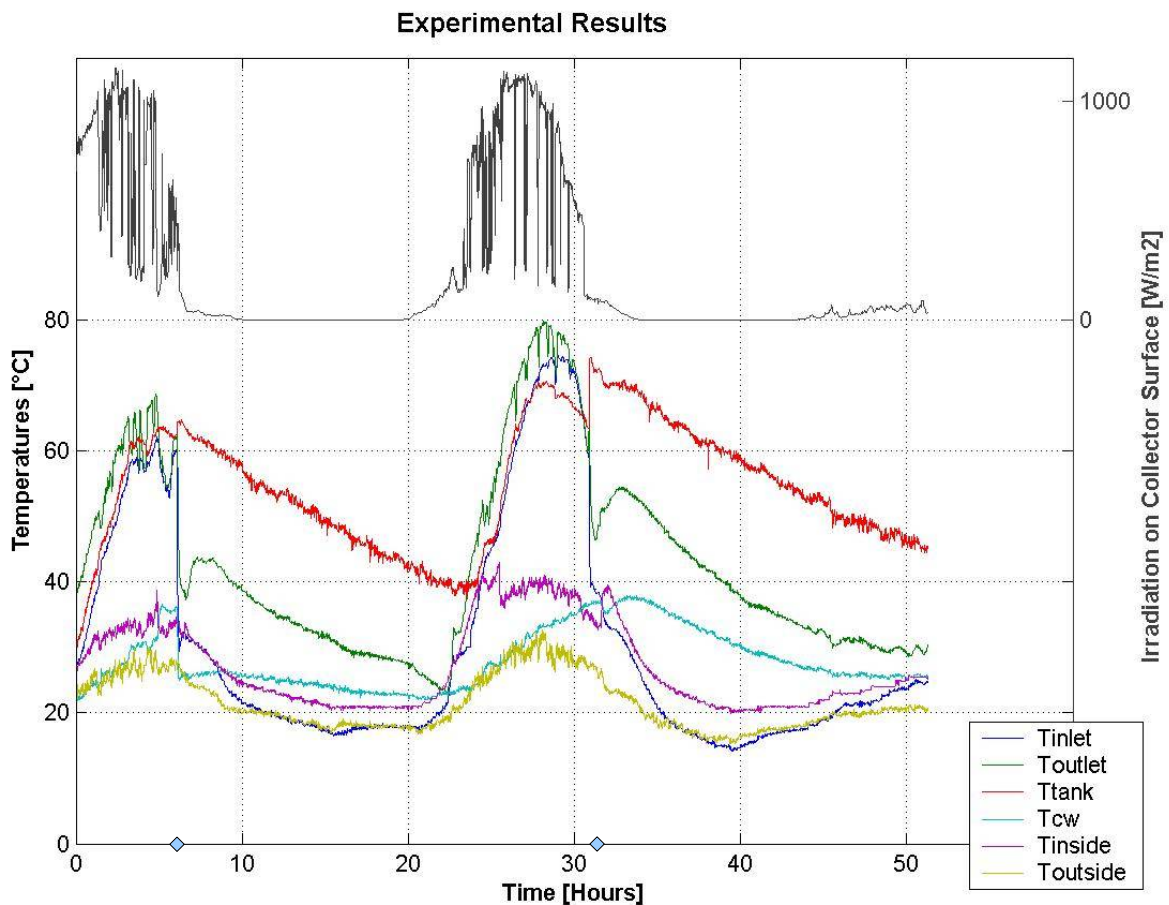
On an edge of the thermal collector is fixed a pyranometer with the same direction and slope. Doing it, we measure the global solar irradiance I on the collector surface with an uncertainty of $1\text{W}/\text{m}^2$.

We use type T thermocouples in order to measure the temperatures in several points of the system. Two wires of different materials (one in copper and the other in copper-nickel alloy) are linked together on the measurement point, a low voltage proportionate to the temperature is created between the two wires. We measure the temperature of water in the inlet T_{inlet} and in the outlet T_{outlet} of the collector, in the top the tank T_{tank} , in the cold water tank T_{cw} , and the ambient temperatures inside T_{inside} and outside $T_{outside}$ the greenhouse where the machine is placed. These sensors have a satisfactory uncertainty of 0.2°C .

All these sensors are connected to a database software which saves the data every minute. We use the software MATLAB to process data and to draw the graphs.

Two records were made in August 2010 during sunny days. The washing program was run everyday in the middle of the afternoon (blue lozenge on the time axis). During the experiences, the 4-ways valve is on “cold” position (machine supplied with cold water) except when the vessel is filling the first time (washing cycle). In this case the valve is on “hot” position.

III.2. Thermal results analysis



Experience from the 13th August 2010 10h55' to the 15th August 14h00'

At first we observe the irradiance on the collector. During the two first hours, the solar irradiance regularly increases from 700 to 1000W/m², it means that the sky is without clouds. The rest of the day 1 and the whole day 2, it follows a profile of sunny days (with a maximum of about 1100W/m²) with cloudy spells (when the irradiance drops to 200 or 300 W/m²). The third day is rainy and cloudy, the irradiance does not exceed 100W/m².

The outside ambient temperature agrees with summer days with a maximum of 32°C at 2pm day 2 and a minimum of 15°C the night after the day 2. The temperature inside the greenhouse oscillates between 40°C during day and 20°C during night. The cold water temperature oscillates between 25 and 35°C.

The temperature on the collector inlet increases since the sunrise and has a maximum of 75°C at 4pm day 2. When the machine starts (blue lozenge), we reload the system through the collector with a water coming from the cold water tank. At this moment, we observe that the inlet temperature suddenly drops to a value close to the cold water temperature.

During night the fluid in thermosiphon does not flow and so the inlet temperature is equal to the outside ambient temperature.

The temperature on the collector outlet has the same profile as the inlet. It is directly influenced by the solar irradiance and small drops appears on the temperature curve during cloudy spells. It is few degrees higher than inlet temperature until this last one reaches its maximum. At this moment the outlet temperature decreases until joining the inlet temperature. This phenomenon appears when the collector reaches its stagnation point : the temperature of the collector is so high that the thermal losses compensate the solar energy input, efficiency is nil, so inlet and outlet temperatures are equal.

During night we observe a behavior different to inlet temperature. We explain that because the thermocouple is placed inside the greenhouse at the level of the inlet of the tank. So it measures the temperature of the water in the tank at the 2/5th of its height.

During day, on the top of the tank the temperature is almost similar to the inlet of the collector. After reaching its maximum, it decreases slowly until the next sunrise. The slope of this fall is function of the heat transfer coefficient of the tank.

We observe the following phenomenon during the day 2 : the top of tank temperature decreases before the stagnation point and suddenly increases from 65 to 75°C when the machine turns on. The thermocouple is placed on the top of the vertical tube (highest level) going out from the top of the tank to the 4-ways valve. It might be that the hottest water of the system (75°C) stays inside the tank and flows in the tube to the mixing valve only when the vessel is filling up. So, if we want to properly measure the maximum temperature of the system, the sensor must be placed in the tank. Maybe this phenomenon only happens with flat-top tank, proper water tank are usually with curved top and bottom.

III.3. Thermal system efficiency

If we make the energetic balance of the system, we have only inputs from solar irradiance $I(t)$ which comes during a Δt duration. A part of this thermal energy is lost depending on the efficiencies of the different elements : the collector (η_{coll}), the tubes (η_{pipes}) and the storage tank (η_{stock}). The product of these three ones is the global thermal system efficiency η_{syst} . The thermal energy finally obtained represents a mass m of fluid, initially at the temperature $T(0)$, and now at the temperature $T(\Delta t)$.

$$\eta_{syst} \cdot S \cdot \int_{t=0}^{\Delta t} I(t) \cdot dt = m \cdot Cp \cdot (T(\Delta t) - T(0))$$

with S [m²], I [W/m²], t [s], m [kg], Cp [kg/J/K], T [K].

III.3.1. Optimum efficiency

The efficiency of tubes only depends on the difference between the fluid and the ambient temperature. The warmer the fluid is, the lower the efficiency is.

The storage efficiency depends on the fluid temperature and also on the storage duration. When there is no input, the longer the hot fluid stays in the tank, the more energy it losses.

The collector efficiency depends on solar radiation and on its internal temperature. The more the sun shines, the more efficient the collector is, but the warmer it is, the more energy it losses. A simple expression of the efficiency of a solar thermal collector introduces two constants : an optical factor A and a thermal losses factor B in W/m²/K.

Here above is the calculation of the global thermal system efficiency η_{syst} with A , B , $C1$, $C2$ and D which are positive constants.

$$\begin{aligned}\eta_{coll} &= A - \frac{B \cdot \Delta T}{I} \\ \eta_{pipes} &= -C1 \cdot \Delta T \\ \eta_{stock} &= -C2 \cdot \Delta T - D \cdot \Delta t\end{aligned}$$

$$\eta_{syst} = \eta_{coll} + \eta_{pipes} + \eta_{stock} = A - B \cdot \frac{\Delta T}{I} - (C1 + C2) \cdot \Delta T - D \cdot \Delta t$$

Thanks to this last expression, we can see that the efficiency of the system is optimum for :

- a maximum solar radiation
- a fluid temperature close to ambient temperature
- a minimum storage time

In order to approximate this optimum efficiency, we use the data of the two first hours of the experience below. During this short time τ , the irradiance was high and stable, and the water is cold at the beginning because it was just inserted into the system.

The global capacity of the system (tank + tubes + collector) is 33 liters, so the global mass m_t of liquid is 33kg. The water, initially at 28.7°C have been warmed up to 59.3°C. With the numerical integration of the irradiance during this time, we find the optimum efficiency of the system.

$$\eta_{max} = \frac{m_t \cdot Cp \cdot (T(\tau) - T(0))}{S \cdot \int_{t=0}^{\tau} I(t) \cdot dt} = 61 \%$$

An optimum efficiency of 61% is good for a first prototype which has been totally constructed in the laboratory workshop. Knowing that the optical factor of a self-constructed collector is almost the same as a standard thermal collector (about 70%), the thermal losses of the whole system (in these optimum conditions) are only 10% of the solar energy available on beginning.

III.3.2. Daily mean efficiency

During the collector surface design, we have shown that a simple method permit to directly calculate the collector surface depending on the hot water needs, the temperature needs and the daily mean radiation :

$$S = \frac{C n V (T_{max} - T_{min})}{K_i E d}$$

where $C = \frac{\rho Cp}{3.6 \eta_d}$

The daily mean efficiency η_d is the constant to experimentally determine on our prototype. It represents the system efficiency during 24 hours. We calculate it with the energetic balance expression during a period of 24 hours which starts when the machine is switched on. At this moment a water mass m , equal to one washing cycle need (12kg in our case), draws from the tank to the vessel of the washing machine. The same quantity of new cold water (temperature : T_0) is inserted in the thermosiphon loop. We named T_{24} the temperature of the water available on the top of the tank 24 hours later.

$$\eta_d = \frac{m_t \cdot Cp \cdot (T_{24} - T_0)}{S \cdot \int_{t=0}^{24h} I(t) \cdot dt}$$

We calculate this efficiency for three days of the two experiences realized.

	Experience 1 (Day 1)	Experience 2	
		Day 1	Day 2
Inserted cold water T°	27°C	30°C	31,5°C
Available hot water T° after 24h	75°C	80°C	74,5°C
Radiation during 24h	5,7 kWh/m ²	6,4 kWh/m ²	6,1 kWh/m ²
Daily efficiency	16,8 %	15,7 %	14,1 %

First positive point is that the three value are close together. Their values are much lower than the optimum efficiency. In fact in the present conditions the time factor is higher and the radiation factor is lower (because of night).

It is difficult to explain the differences between the values of the experiences. The relation with the temperature of water is true : the colder the inserted water is, the higher the efficiency is. But the radiation has not representative influence on the calculated values of efficiency.

We must go further into the influence of the time, temperature and radiation factors in order to obtain a better approximation of the collector surface. Now, choosing a value of 15.5% for the daily mean efficiency, we get this design expression :

$$S = \frac{7.5 n V (T_{max} - T_{min})}{K_i Ed}$$

with n [-] the number of washing per day, V [L] the capacity of the vessel, T_{max} and T_{min} [°C] the respectively hot and cold temperatures, K_i [-] the correction coefficients, and Ed [Wh/m²/day] the daily mean radiation.

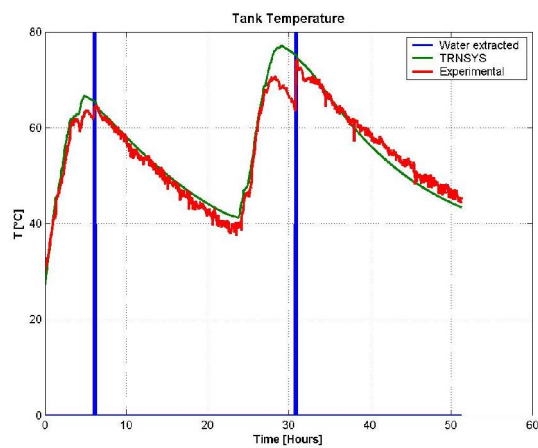
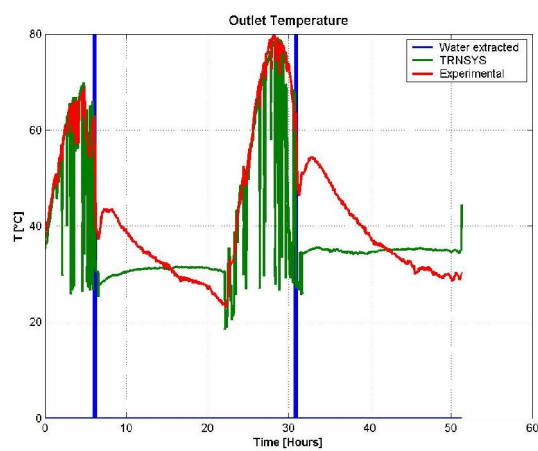
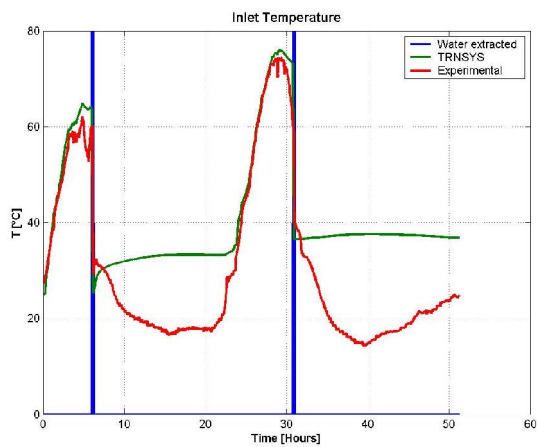
This expression gives us a surface of 1.1m² for one washing a day with 12L at 80°C, initially at 20°C and a mean radiation of 5000 Wh/m²/day. This mean radiation is estimated on a summer period in Witzenhausen, the winter period is useless because of frost. The choice of the mean radiation in developing countries is easier because the climate is almost always the same except during the short raining season.

III.4. Comparison with TRNSYS

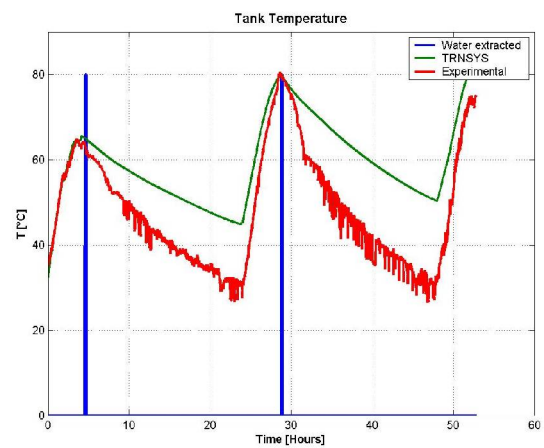
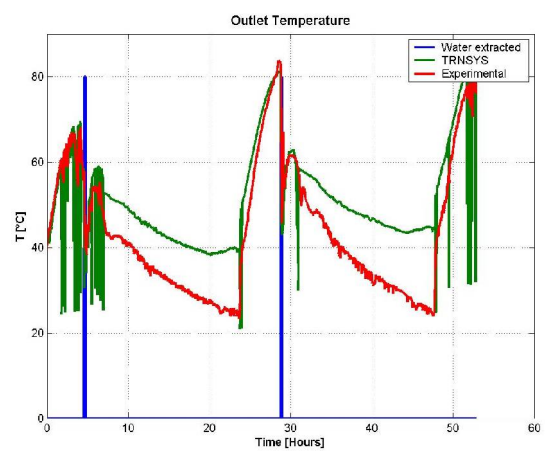
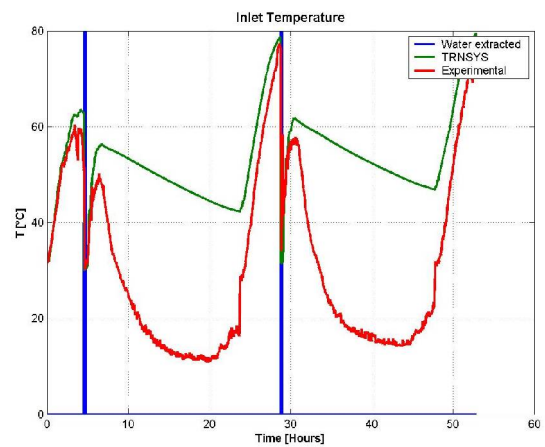
To compare the experimental results with the ones of the TRNSYS simulation is interesting to go further in designing the solar thermal system. In fact, if the calculation model of the software gives similar results as the prototype, it can be used to design a system with irregular needs or variable weather as in Europe.

The TRNSYS inputs (solar irradiance, inside, outside and cold water temperatures) are the experimental measurements. The parameters of the system are the same as in the design simulation, they are the ones of the prototype. The outputs of TRNSYS (inlet, outlet and top of the tank temperatures) are exported into MATLAB to draw the comparison graphs.

1st experience



2nd experience



Comparison of temperatures of the collector inlet (top), the collector outlet (middle) and the top the tank (down) between experiences and TRNSYS simulation

Firstly, if we only look at the first experience, the simulation results (in green) are close to the experimental results (in red) during day. They differ a little bit for the high temperatures on the

collector inlet and on the top of the tank. The outlet temperature of the model is almost the same (during day), except when clouds appear : the drops of the temperature are bigger than in reality. But during night, the software follows a model which differs from reality. The profiles of the inlet and outlet temperatures are completely different. However, it has no consequences on the next day and on the calculation of the temperature of the water stored in the tank.

During day, the differences between simulation and reality are the same in the two experiences. But, on the evenings of the second experience, all the temperatures decrease faster than the predictions of the simulation. So, we see big differences for the second day and we guess that it is worse for the next days.

In the spite of the precautions, it seems to be that the two experiences have not run in the same conditions. Or maybe one parameter not noticed in the simulation have a big influence on the system.

Anyway, not enough experiences were performed to confirm that the thermosiphon model of the TRNSYS software is similar to the reality of our prototype. Some other experiences must be performed.

Some parameters of the collector (optical factor, losses factor) were not experimentally determined and maybe they make the simulation results distorted.

Another solution to precisely predict the thermal behavior of the solar washing machine would be to realize a proper calculation program, and to validate it with the experimental results.

IV. ASSESSMENT


IV.1. Environmental assessment

IV.1.1. Carbon emissions and primary energy saved

The primary energy represents the amount of energy used to extract, to transform and to transport the final energy consumed. Depending on the type of energy, the ratio of primary energy to final energy differs. In France, depending on the ADEME norms, the ratio is 2.58 for public electricity and is 0 for any renewable energy which is locally produced. The same norm says that 1kWh of final electrical energy emit 0.18kg of carbon into the atmosphere.

Our solar washing machine works only with solar energy. So, it consumes no primary energy and it emits no greenhouse gas. If we based on the measurements of this study, a conventional washing machine consumes 1.3kWh of final energy for a “normal” program, 60°C with 5kg load.

We interest now in the environmental impact which would realize a family with two children if they replace their conventional washing machine by a solar one. My mother, who was washing supervisor in a family of this size during several years, told me that she was washing in average a 5kg load every two days, so 183 times a year. Basing on it, a two-children family consumes 238kWh of final energy every year in order to wash their clothes. If we estimate the life duration of a conventional washing machine at 15 years, the global consumption of the machine is 3570kWh of final energy, so 9200kWh of primary energy (equivalent to the energy of more than 6 barrels of petrol) and 642kg of carbon emissions (equivalent to almost 2 barrels of petrol).

Primary energy saved	Carbon emissions saved
9200 kWh 	642 kg 

Approximation of the primary energy consumption and carbon emissions of a conventional washing machine during 15 years in a two-children family

IV.1.2. Water and environment

A washing machine consumes about 50 liters of water. It represents every year 9m³ for a two-children family. According to the *Agence de l'eau*, the France receives every year 900 liters of rain water per square meter. So, we see that a surface of 10m² to get back rain water in enough in France to supply a washing machine.

In conventional washing machines, waste water is polluted by chemical soaps. It exists now ecological ways to wash clothes (washing nuts, ceramic balls). Anyway, today every occidental family throw away almost 10m³ of water every year with their washing machine. This waste water can be reused for an agricultural use to irrigate adapted plants.

In the case of the installation in remote areas in developing countries, the problem is different because water (even from rain) is very rare. It exists some technologies to get back water from dew. The waste water can be disinfected and reused. For example, it exists solar disinfection systems.

IV.2. Economical balance

We interest here in the economical balance in Europe. Using the yearly consumptions calculated above and knowing the European mean price of electricity (*Eurostat* : 15,3c€/kWh) and of water (*Nus Consulting* : 3,44€/m³), we estimate the cost of using a conventional washing machine for a two-children family at 70€ per year.

Estimating the prices of the components to add to a conventional washing machine in order to transform it into a solar one, we can know how long the user will recoup the investment.

The price is calculated for a model similar to our prototype, which can realize one washing at 80°C every day.

Component	Price (€)
Solar thermal collector 1m ²	300
Photovoltaic panel 50W	300
Battery 100Ah and charge regulator	200
Hydraulic components, tank	300
Motor 24VDC	150
Pump DC	30
Electronic components	50
Total	1330 €
Amortization	19 years

Estimation of price and amortization of a domestic solar washing machine

We can clearly see that the investment has a too long amortization to be attractive in the domestic use. Price of solar equipment represents 70% of the global price. To have a washing machine with two inlets and to connect one of them to a domestic solar water heater will reduce the electrical consumption and will make a good ecological and economical alternative.

Many possibilities are possible to reduce the cost and to adapt it to the remote areas in developing countries. An old washing machine which does not work anymore can be reuse because all the components are changed. The motor, the pump, the solenoid valve and the battery can be reused from old cars. The thermal collector can be self-constructed.

In this way, a solar washing machine costs about the same price as a new conventional one. Then there is no cost for electricity and water.

In Europe, the washing machine can be interesting for collective use (laundrette, hospital, building). Solar devices have decreasing prices scale. The investment is quickly recouped with the payments of the users in the case of a laundrette.

V. PERSPECTIVES

The technology of the solar washing machine is still not ready to be manufactured or installed in developing countries. The calculation methods of the collector surface can be improved, the real electrical consumption must be foreseeable, the electronic card must be reliable to realize a specific printed card. The possibility of connecting the machine to a public water network must be studied. Finally, a specific waste water recycling system can be developed.

V.1. Modifications to the machine

At the end of my internship (September 2010), the prototype does not work perfectly. Some problems must be analyzed to find some solutions.

V.1.1. Solenoid valve

When we stop powering the solenoid valve, a small flow of water still goes through during a long time. It means that the vessel continues to be filled up during spinning cycle and also after the end of the program.

Here are the possible causes of this problem :

- Maybe this solenoid valve has a problem and only change it will solve the problem
- Maybe some dirt is in the valve. It has to be cleaned and a filter must be installed upstream
- Maybe the valve is installed in the wrong direction
- Maybe the “OFF” position of the valve is not well adjusted. Some valves have a manual adjustment

V.1.2. Electronic components

The D flip-flop and the counter do not work as it would be.

The flip-flop is powered with 5V instead of 12V and do not control the relay regularly.

The counter does not work at all. The clock input (pin 15) is linked to the “0” position of the relay S2. It should count the number of rising edge on this wire, equivalent to the number of starting of soaking cycles. The four outputs (respectively pins 2, 14, 11 and 6) are the four bits of the binary counted number. Linking the pin 14 to the relay S0, this relay should switch on when the fourth (0100 in binary code) soaking cycle starts. We observe no change on the levels of the four outputs whatever the number of soaking cycles.

The electronic schema of the prototype must be analyzed by electronic experts in order to solve these problems or maybe to change some electronic components. I have made an interactive explanation of the working of the electronic card.

V.1.3. Diodes

When we tried the washing machine, we have measured a current higher than 10A during washing cycle when the clothes were totally wet. The standard diodes can support at most 10A. So, we stopped the machine to not damaged the components.

It exists power diodes components, including two diodes with common cathode, which can support until 80A. It is possible to fix to these diodes a metal sheet in order to properly dissipate the

warmth.

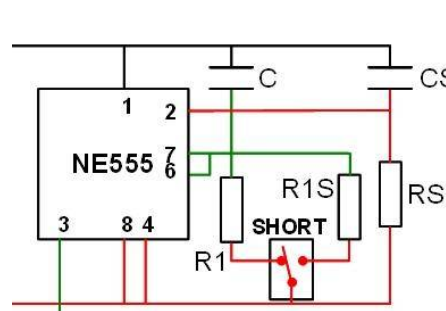
Schottky diodes have a high switching speed, a low voltage drop and a similar price compared to other types of diodes.

So, two Schottky double power diodes with common cathode can replace the four standard diodes of the power circuit.

However, a study of the relation between the mass of wet clothes and the current consumed by the motor is essential to design the characteristics of the diodes and of the motor.

V.1.4. “Short washing” mode

As explained in the electronic design paragraph, a “short washing” mode can be simply added with a manual switch *SHORT* and another resistance *R_{IS}*. The modifications on the timer connected to the relay *SI* are shown below.



“Short washing” mode modifications

If the user switches on the *SHORT* button, the current go through the resistance *R_{IS}* instead of *R_I*. The resistance value is calculated depending on the time of the short washing cycle *t_{short}*.

$$R_{1S} = \frac{t_{short}}{1.1C}$$

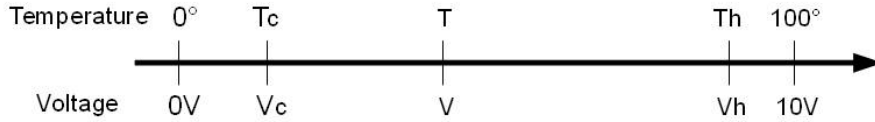
V.1.5. Automatic control of mixing valve

In order to have a complete automatic washing machine, it is necessary to control the 4-ways valve with an electronic system.

It exists some actuators to motorize valves, for example the ARA659 of ESBE. This device can be powered with 24VDC and can control valves using a signal which is proportional to the angle of the valve. This controller has 3 pins : two for the 24VDC power and one for the proportional control signal : 0V for 0° (coldest water) and 10V for 90° (hottest water).

A new electronic system must be installed to send the signal *V_S* to the actuator. The user sets the washing temperature *T* with a variable resistance rotary button *R* before switching on the machine. The two extreme temperatures of this button are *T_{min}* and *T_{max}* (for example 20°C and 80°C). Two thermocouples measure the temperatures *T_c* and *T_h* of the cold and of the hot water.

The idea to make the relation between the measured temperatures and the selected temperature is to create a voltage scale which is the tenth of the value of the temperature in Celsius degree (0V=0°C, 10V=100°C).

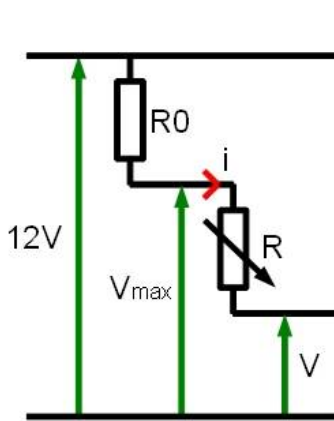


Temperature-voltage scale

The relation between the temperatures T_c and T_h and the voltages V_c and V_h depends on the thermocouple constants α and β .

$$V_{c,h} = \frac{\alpha T_{c,h} + \beta}{10}$$

Then, we get the voltage V from the temperature T in using a simple circuit with resistances.



$$V_{max} = \frac{T_{max}}{10}$$

$$R_0 = \frac{120 - T_{max}}{10i}$$

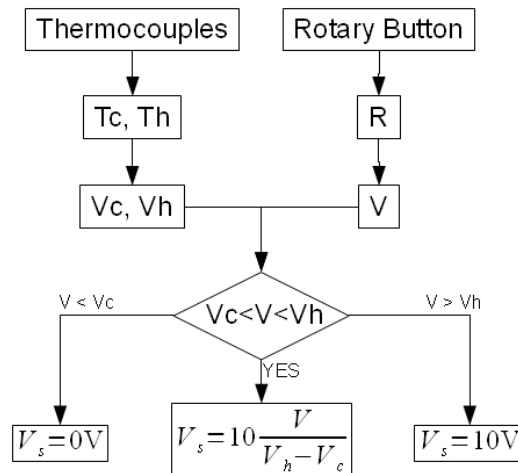
If $R=0$, $V=V_{max}$, the temperature is set to T_{max} .
 If $R=R_{max}$, $V=V_{min}$, the temperature is set to T_{min} .

$$V_{min} = \frac{T_{min}}{10}$$

$$R_{max} = \frac{T_{max} - T_{min}}{10i}$$

Circuit with rotary button

Then, we have all the elements to create the control signal V_s sent to the actuator.



Schema of the automatic valve control process

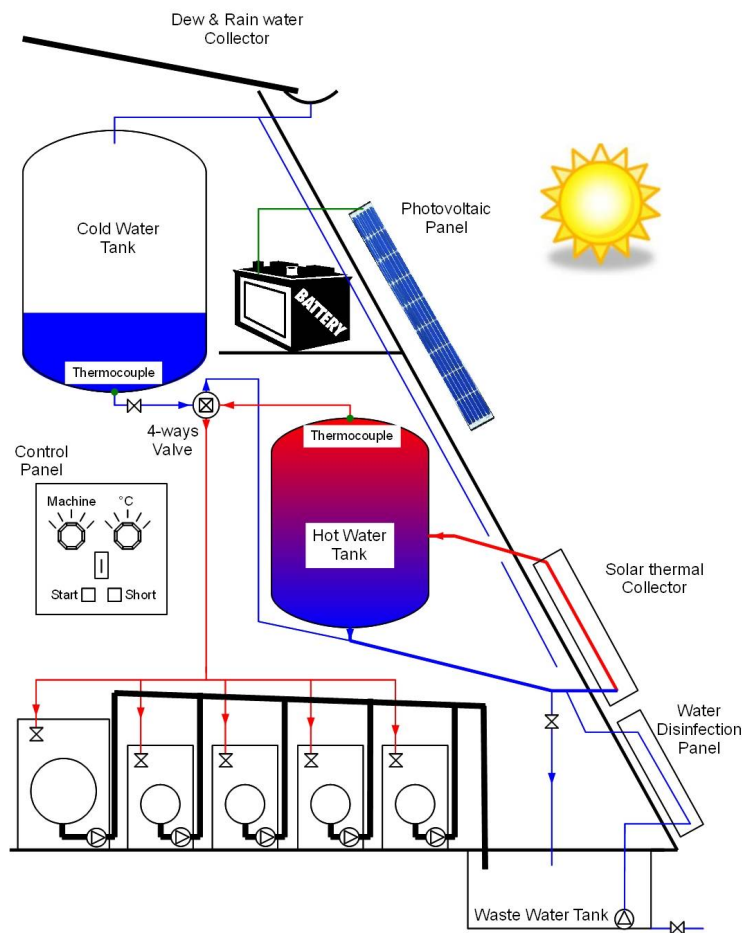
These functions can be realized only with electronic components, operational amplifiers and multiplier. Several modifications have to be done on the electronic card to include this system because the actuator must be powered with 24VDC before the filling of the vessel for the washing cycle. The valve also needs to come back to cold water position before starting the first soaking cycle.

V.2. *Solar laundrette*

A laundrette is a public place where people can wash their clothes. As the economical assessment shows, the solar washing machine concept is more attractive for collective use. A solar laundrette permits to wash the clothes in an ecological way. Using only solar energy, this concept protects the planet and can make the washing cheaper than in conventional laundrette. This chapter will show four possibilities of solar laundrette : one totally self-sufficient adapted to the developing countries ; one with a system which get back the warmth of the waste water without consuming energy ; one more adapted to the occidental countries ; and the last one more economic.

V.2.1. *Self-sufficient laundrette*

The self-sufficient solar laundrette is designed for the remote areas in developing countries. It needs no connection to the national grid or to the water public network, it gets back water from the air and recycles the waste water. Its working is shown below.



Schema of the self-sufficient laundrette

The water of all the machines is warmed up in the same tank by a thermosiphon between the solar thermal collector and the hot water tank. Electricity is created with photovoltaic panels and stored in batteries.

All the machines are powered through the control panel. From this place the user selects the machine that he wants to use, the washing temperature, the program (short or not), and then he presses the “start” button. The actuator sets the 4-ways valve to get the good temperature and then the machine is powered. During a program, another user can wash its clothes with another machine, the control panel must include a priorities system to not send two different signals to the actuator exactly on the same time.

Comparing with the solar washing machine, there are two new technologies in the solar self-sufficient laundrette :

- **Dew and rain water collector**

The dew and rain water collector is developed and patented by Marc Muselli from the university of Corsica. This panel is covered with a specific paint which has the property to assembly the water drops together. In this way, the drops from dew become bigger and slide down to the gutter and then to a drain pipe which bring the water to the cold water tank. Of course, the rain water is also collected.

This system is very useful in countries where water is rare. Moreover it needs no energy to work.

- **Solar water disinfection panel**

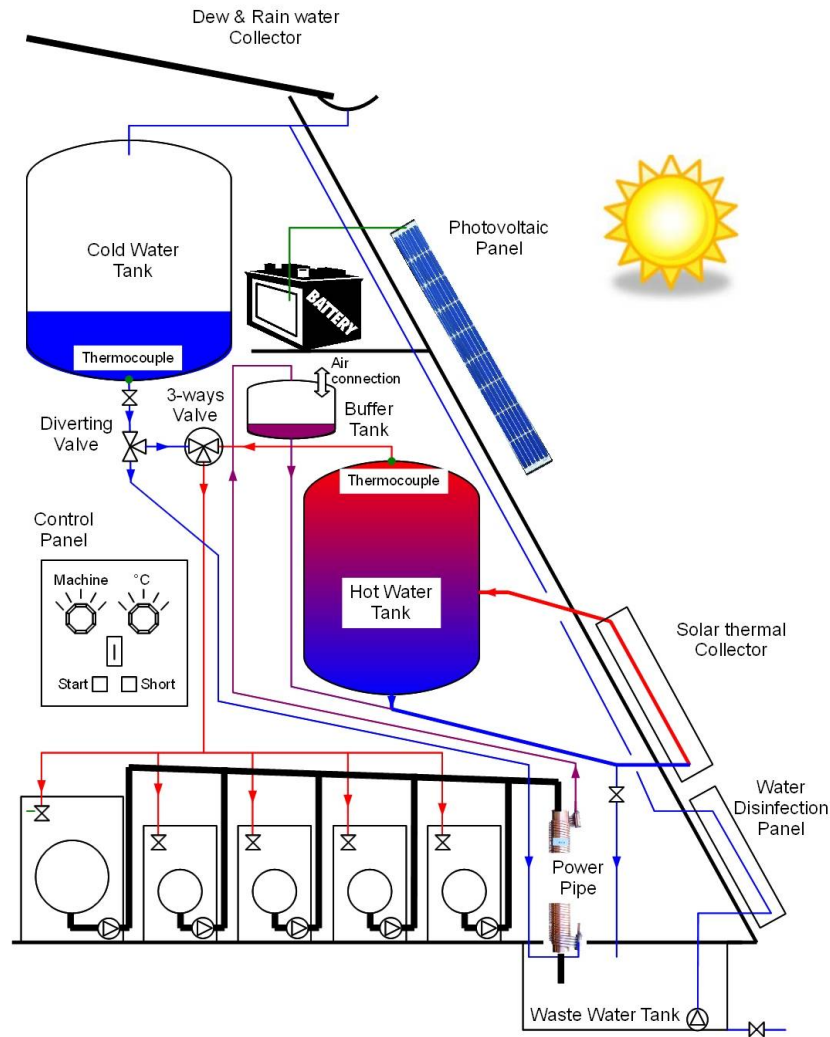
If the water from rain and from dew is not enough to supply the laundrette, it is possible to reuse the waste water. Several systems exist. One of them uses the ultraviolet rays of the sunlight to disinfect water. Waste water is stored in a tank, then it flows to the panels with a pump. The flow rate can be adjusted depending on the irradiance and on the amount of pollution in the water.

V.2.2. The Power-Pipe[®]

The Power-Pipe[®] is a Canadian technology in order to get back the warmth from the waste water without energy input. It can save a lot of energy and so reduce the solar thermal installation. The Power-Pipe[®] is a vertical copper drainpipe, with another copper pipe rolled around. The warm waste water flows down along the walls of the drainpipe. It exchanges its warmth with the cold water which flows up in the rolled pipes.

The main problem to adapt this technology to the washing machine is that during a program the machine never draws hot water on the same time as it drains hot waste water. So we need to include a buffer tank which contains the water preheated by the Power-Pipe[®] during the drainage of washing cycle.

We have to change the 4-ways valve mixing system if we still want to mix the cold water and the solar hot water. We use now a diverting valve and a 3-ways mixing valve. In this way, cold water is preheated during the drainage of the washing cycle, stored in the buffer tank, and inserted in the thermosiphon during the next filling of washing cycle. The buffer tank must be isolated to keep the warmth of the water as long as possible. It must also let the air going in and out without letting the water going out.



Schema of the self-sufficient laundrette with the Power-Pipe®

The table below shows the configuration of few elements along the washing program.

Element	Washing cycle		Soaking cycle		Spinning cycle or OFF
	Filling	Drainage	Filling	Drainage	
Diverting valve	To valve	To Power-Pipe®	To valve	To valve	To valve
Buffer tank	Emptying	Filling	Full	Full	Full
3-ways valve	Hot	---	Cold	---	---
Machine solenoid valve	ON	OFF	ON	OFF	OFF

The best case is if a second machine starts just after the drainage of the first one because the water in the buffer tank, which has been preheated just before, is inserted in the thermosiphon.

If a second machine starts during the washing cycle of the first one, it is possible that the buffer tank is empty. In this case the diverting valve must supply the buffer tank through the Power-Pipe® in

addition to the 3-ways valve.

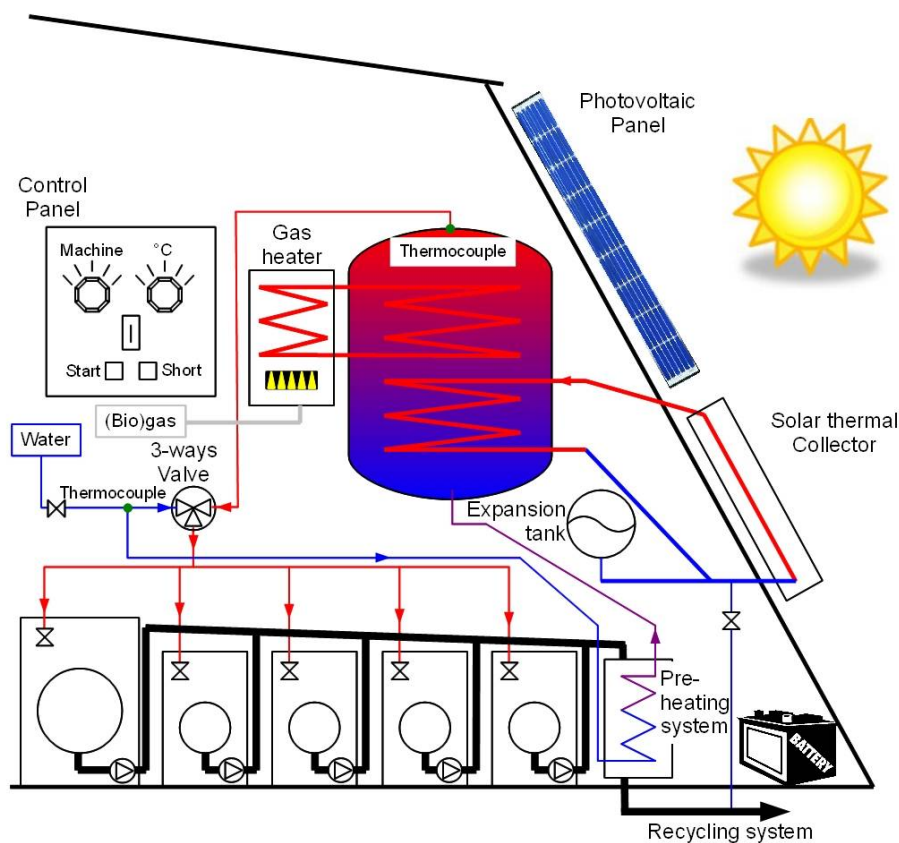
The buffer tank can be full if several machines drain the hot washing cycle water before that one starts a washing cycle. This case has no consequences except that the Power-Pipe[®] will not be used. To set the level of the buffer tank it is possible to control the valve on the bottom of the thermosiphon loop to remove colder water and let the preheated water come in the thermosiphon.

The Power-Pipe[®] can maybe save a lot of energy but it needs more elements and more automatic control. We need to work further on its usefulness in the laundrette.

V.2.3. Solar laundrette for occidental countries

Design a solar laundrette in occidental countries is completely different to developing countries. The aim is to create a place which has the same benefits as a conventional one, where the users can wash their clothes in an ecological way.

The inhabitants of these countries do not want to change their habits because the laundrette uses a solar technology. For example, if the laundrette does not permit them to wash their clothes at 60°C during a cloudy day in winter, they will never come back in this place. Some people also do not want wash their clothes with rain water.



Schema of the solar laundrette for occidental countries

Water inlet comes from the public network. The thermosiphon has now an exchanger in the hot water tank. Frost-resistant fluid flows in this loop. An expansion tank is added.

If the solar energy is not enough to warm up the water, an additional heater can be used. This laundrette is not connected to the national grid, the electricity comes from the photovoltaic panels. An electrical additional heater would need too much energy compared to what can produce the

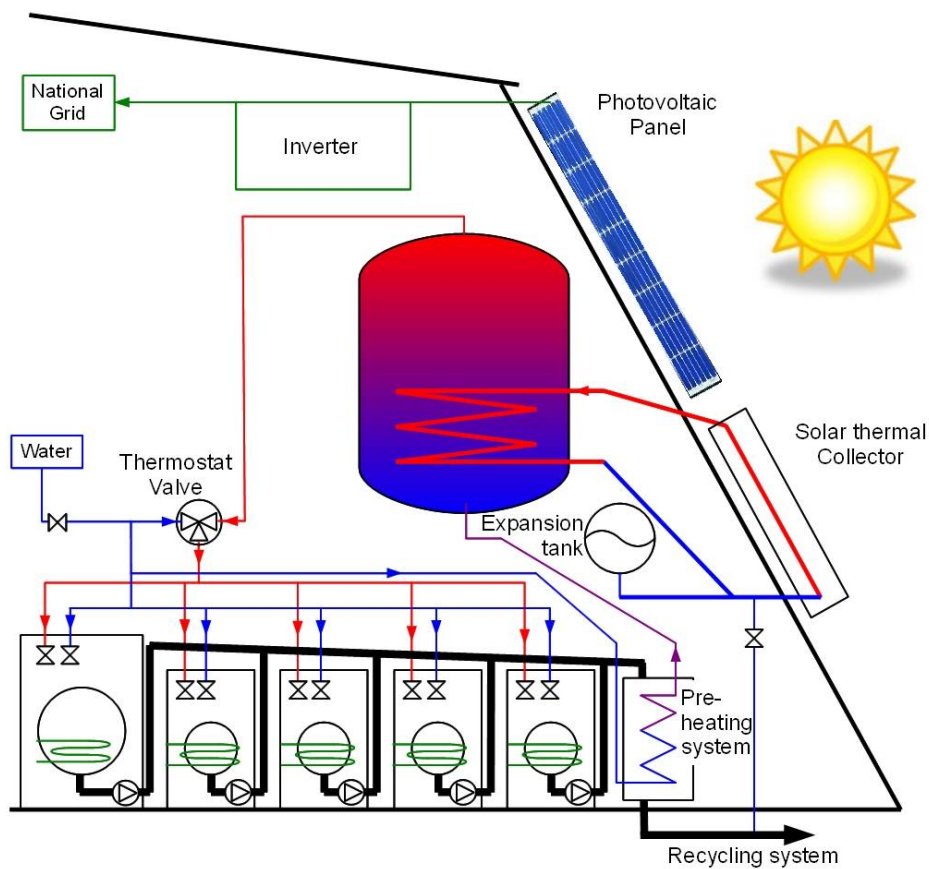
photovoltaic panels in winter. So we choose here the gas energy to warm up the water in the upper exchanger. Supplying this heater with biogas is the most ecological solution.

A preheating system which get back the warmth from the waste water can be added in order to reduce the solar thermal installation. The Power-Pipe® can not be used here because the hot water network is under pressure and the buffer tank needs to be open to the atmospheric pressure. Other systems exist and do not need that hot water is drawn on the same time as it is drained. They use heat pump technology and so they need electricity to work.

The recycling system can simply be plants which disinfect the water.

V.2.4. Economical solar laundrette

As the economical balance has shown, the solar washing machine is expensive. This last possibility shows a laundrette connected to the national grid, using conventional washing machine.



Schema of the economical solar laundrette

Instead of being stored into batteries, the photovoltaic electricity is transformed in an inverter and sold to the electricity national company. This solution permit to create the same amount of consumed electricity with renewable energy, and to earn money because the electricity is bought more expensive than it costs.

If the solar system is not enough to warm up water, the electric heaters of the machines adjust to the good temperature. In this case, it is better to use machines with two inlets. The user sets the washing temperature with the thermostat valve and with the thermostat button of the machine.

This solution is very easy to install but does not use the innovative and simple 12V washing machine.

The table below shows the characteristics of the four possibilities of laundrette :

Characteristics	Self-sufficient laundrette	Self-sufficient laundrette with Power-Pipe®	Occidental countries laundrette	Economical laundrette
Water inlet	Rain & dew collector	Rain & dew collector	National network	National network
Cold water tank	Yes	Yes	No	No
Mixing system	4-ways valve	Diverting valve and 3-ways valve	3-ways valve	Thermostat valve
Solar thermal system	Thermosiphon	Thermosiphon	Thermosiphon	Thermosiphon
Hot water tank exchanger	No	No	Yes (frost-resistant fluid)	Yes (frost-resistant fluid)
Additional heater	No	No	Gas heater	Electric heater of machines
Waste water warmth	No	Power-Pipe® (with buffer tank)	Heat pump ?	Heat pump ?
Waste water recycling	Solar disinfection	Solar disinfection	Plants	Plants
Photovoltaic electricity	To batteries	To batteries	To batteries	To the national grid
Inverter	No	No	No	Yes
Control Panel	Yes	Yes	Yes	No
Washing machines	12VDC One inlet	12VDC One inlet	12VDC One inlet	230VAC Two inlets

CONCLUSION

In my personal view, this internship was a very good opportunity to work again in a research laboratory, with a more manual and practical aspect. During these five months, I have learned to lead a project from the idea to the experiences on the prototype, making also the design of every elements and the complete construction. Speaking with students, laboratory members, scientists from the whole world, I have learned a lot about ecologic agriculture, renewable energies and their applications in the developing countries.

The solar washing machine is a huge project which can make better the hygiene of many hospitals, and also save a lot of primary energy in occidental countries if solar laundrette are developed. This machine works with a free and inexhaustible energy. It can be installed in a totally self-sufficient configuration. It has a simpler working than our modern machines, but it is easily customizable to be adapted to a precise use (hot water needs, washing program, construction materials).

There is still a lot of work before opening the first solar laundrette in Europe or in Africa, but I am sure that the desire and the determination of the laboratory workers will make from this witty idea a reality.

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