This document describes the installation of the Ohmpilot from Fronius which is associated to my 3-kW solar generator and a 300-liter electric boiler.

The Ohmpilot is an ac-ac converter which will deliver a 50-Hz alternating voltage continuously adjusted in amplitude from 0 to 100% of the grid value, i.e. 0-230 V rms (nominal) here in France. This voltage will be applied to the electrical resistance of a hot-water tank and will be modulated according to the power available while keeping a 0-W injection into the grid. Indeed, in this mode, we try to consume all the power produced by the solar panels but if this solar power exceeds that absorbed by the house, the inverter adjusts its operating point so as not to inject into the network (so-called 0-W mode). With the Ohmpilot, if the house consumes 650 W and the solar potential, at this moment, amounts to 1.2 kW, there is an unconsumed surplus of 550 W which will be directed towards the tank to store the available energy as hot water. Let's take this example of a 300-liter tank equipped with a 2-kW resistance and assume an Ohmpilot is running:

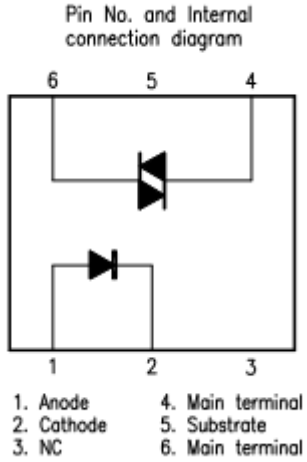
P_{boiler} = 2 kW à 230 V – nominal power
$R = U^2/P = 230^2/2000 = 26.5\ \Omega$ – ohmic value of 2-kW resistance
→ 550 W implies a voltage V = sqrt(P x R) ≈ 121 V rms
The Ohmpilot will adjust its output and applies this ac bias across the resistor, dissipating 550 W

The excess power now increases to 1.3 kW, the Ohmpilot delivers V = sqrt(1.3k x 26.5) ≈ 186 V rms. If the excess power rises to 2 kW, the Ohmpilot delivers 100% of the network power, i.e. 230 V There is no excess, the Ohmpilot delivers 0 V.

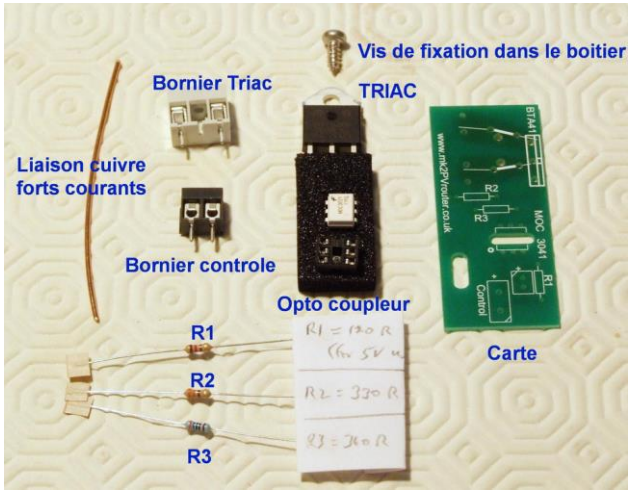
The converter permanently communicates with the inverter which is connected to the installation's energy meter. The latter therefore knows the power absorbed by the house and tells the Ohmpilot how to adjust its power to maintain a 0-W injection.

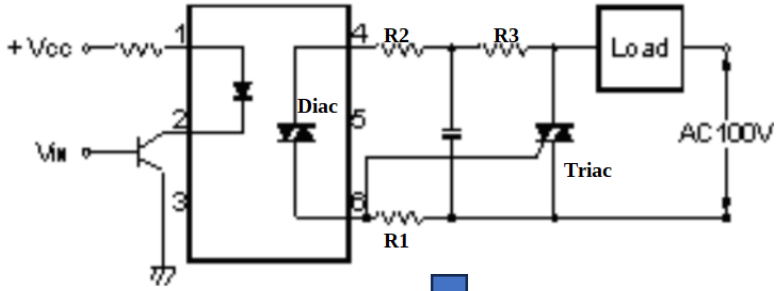
Rms, root mean square

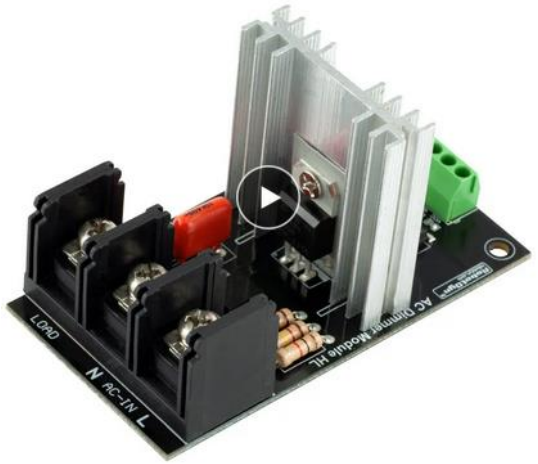
There are “solar routers” – this is the nickname used for these modules – and they are made of triacs controlled by an opto-diac, the MOC3021 introduced by MOT a long time ago:



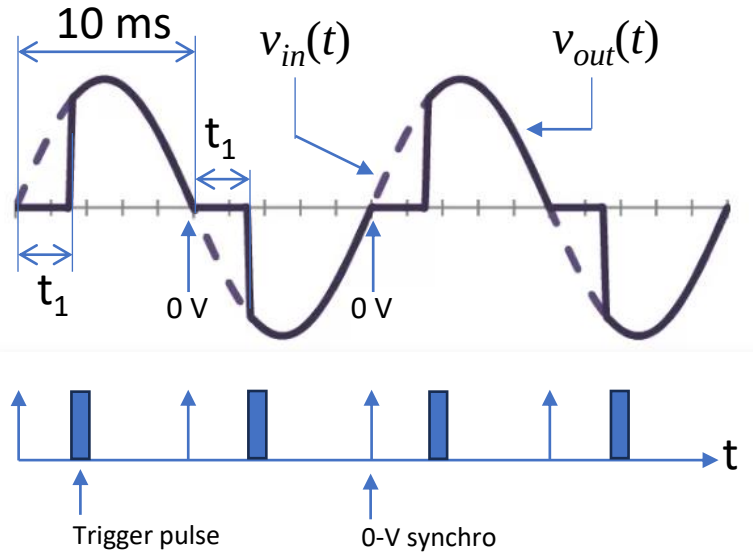
You can either build your module yourself with the numerous tutorials on the web or order it from Ali-Express like this one from RobotDyn (€10 for the 10-A version)





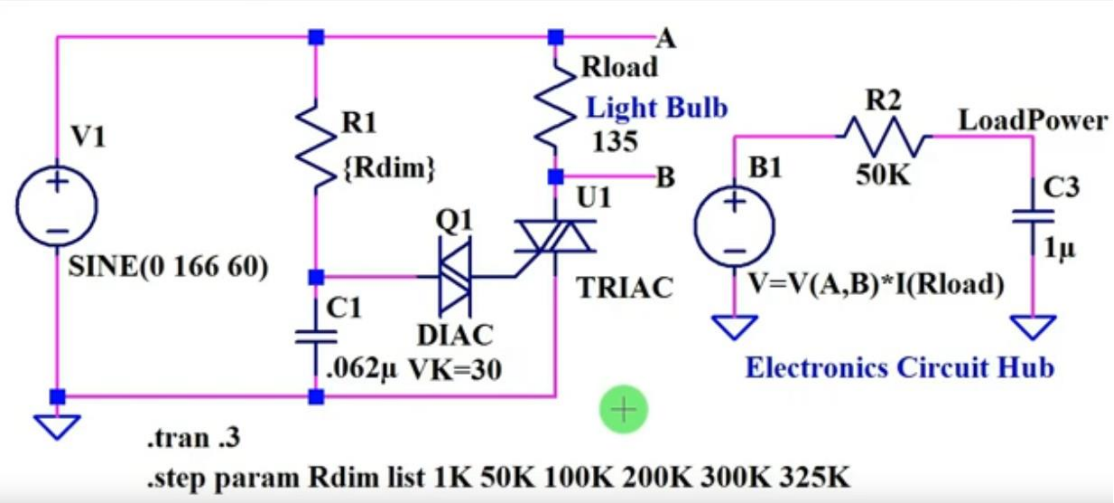


With a micro - usually an Arduino – a pulse is sent at t_1 via the opto-diac which starts the triac. It conducts for (10 ms – t_1) and produces the black waveform.



The micro receives the consumption information via a current clamp and adjusts t_1 to modulate the load power in order to keep 0-W operating mode.

Power calculations around a classic diac and triac dimmer:



This is the classic configuration of a triac dimmer like they were tinkered in the 80s to dim the lights in garage parties. The principle is simple: the network R_1C_1 introduces a pole into the transfer function linking the voltage across C_1 and the network V_1. This pole delays the input voltage V_1 and modifies it in amplitude according to the time constant R_1C_1. A diac is the equivalent of two Zener diodes mounted back-to-back and conducts in both polarities around 32 V. Thus, when the voltage across C_1 reaches ≈ 32 V plus the voltage threshold of the triac (and when the trigger current is met), the triac conducts in quadrant I or III depending on the network polarity. By adjusting R_1, we modify the ignition angle and therefore the effective voltage produced across the load.

Here are the calculations to determine the ignition angle according to the time constant value:

Dimmer components

$R_1 := 33k\Omega$ $C_1 := 100nF$ $V_{th} := 32V$ Diac threshold

$$f_p := \frac{1}{2\cdot\pi\cdot R_1\cdot C_1} = 48.229Hz$$

$$Mag := \frac{1}{\sqrt{1+\left(\frac{F}{f_p}\right)^2}} = 0.694 \qquad \varphi := -\operatorname{atan}\left(\frac{F}{f_p}\right) = -46.033°$$

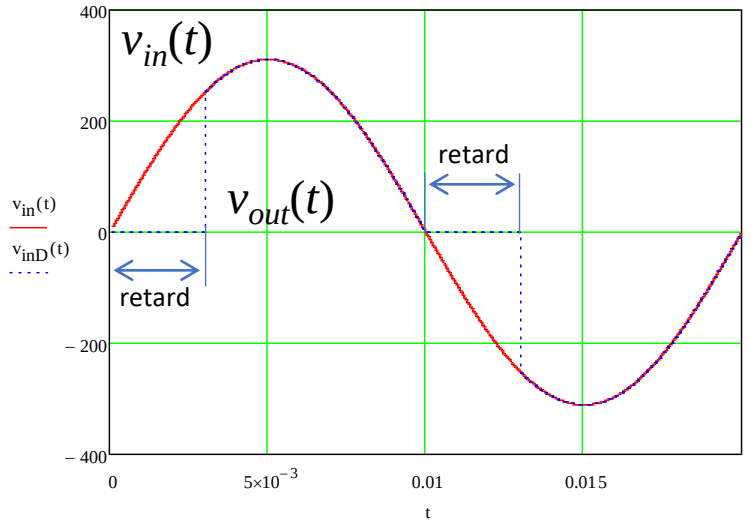
Mag and phase delay of the RC network

$$V_{th} = V_p\cdot Mag\cdot\sin(\omega\cdot t_1 + \varphi)$$

At what time does the voltage reach the diac threshold?

$$t_{del} := \frac{\operatorname{asin}\left(\frac{1}{\frac{Mag}{V_p}\cdot V_{th}}\right) - \varphi}{\omega} = 3.031ms$$

A typical waveform looks like this:



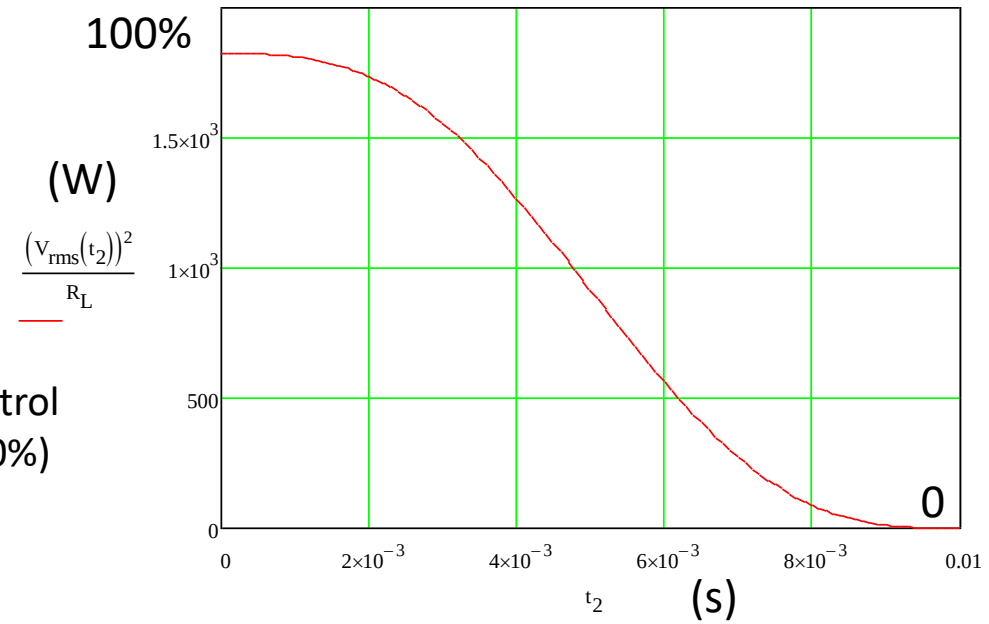
We can now calculate the effective value transmitted to the load and which will vary depending on the chosen angle. With an Arduino, there is no longer a time constant but the angle is calculated in order to exactly adjust the power transmitted to the load (or ensure 0-W injection):

t_1 = 3.03 ms

$$V_{rms}(t_1) = \sqrt{\frac{2}{T}\cdot\left[\int_{t_1}^{\frac{T}{2}} (V_p\cdot\sin(\omega\cdot t))^2\,dt\right]}$$

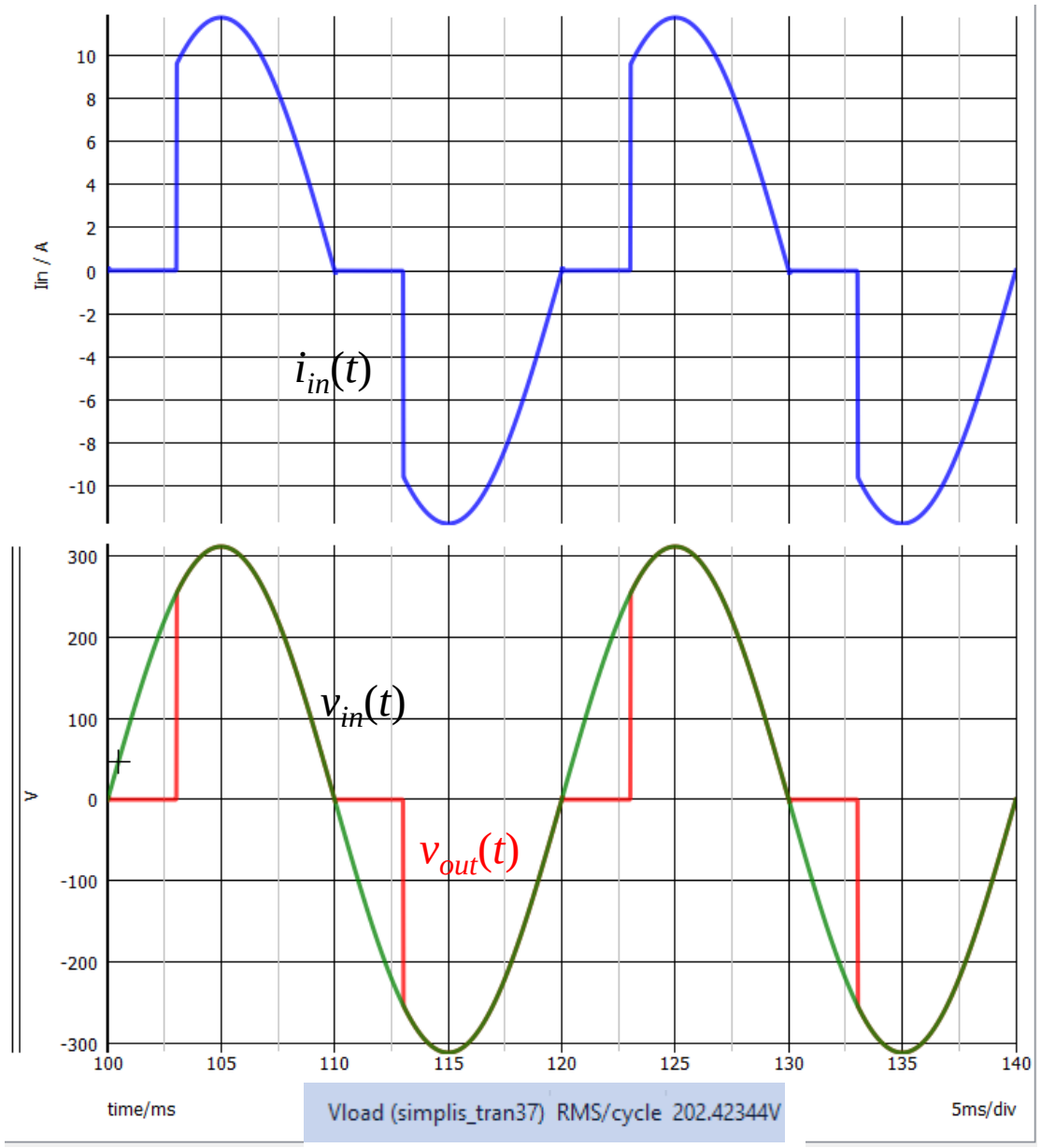
$$V_{rms}(t_1) := \frac{V_p}{\sqrt{2}}\cdot\sqrt{\frac{(\sin(2\cdot\omega\cdot t_1) - \sin(T\cdot\omega) + T\cdot\omega - 2\cdot\omega\cdot t_1)}{T\cdot\omega}}$$

$V_{rms}(t_1) = 202.422\,V$

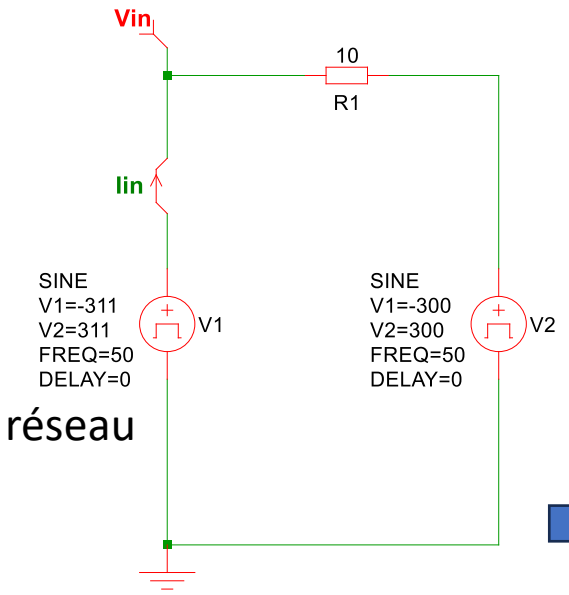


Power versus control angle (2 kW = 100%)

Input current

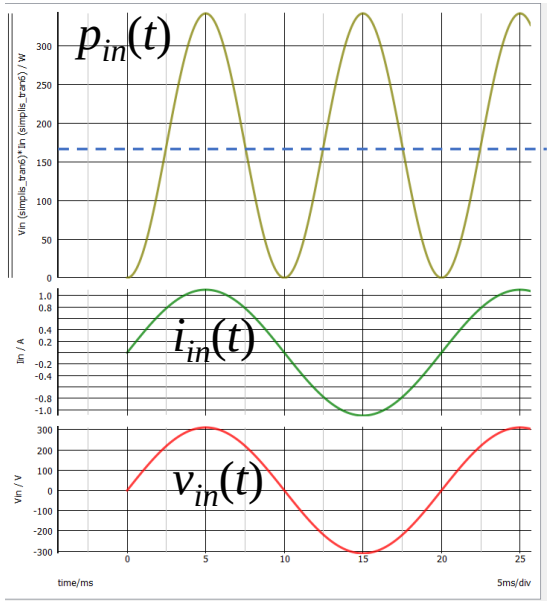


A solar router, whatever its implementation, works to ensure a 0-W injection. We must therefore measure the power absorbed from the network and, depending on its polarity, we know whether the house is receiving or transmitting power.



In this simulation, the right-side source is lower in voltage than that the left one which symbolizes the network. The current flows in phase and the instantaneous power $i_{in}(t).v_{in}(t)$ represents the exchange between the two sources:

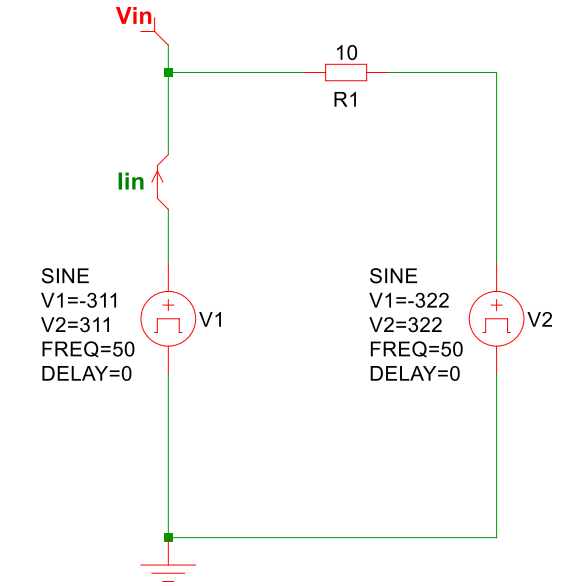
Name	Value
Mean/cycle	171.05W



P_{avg} = 171 W

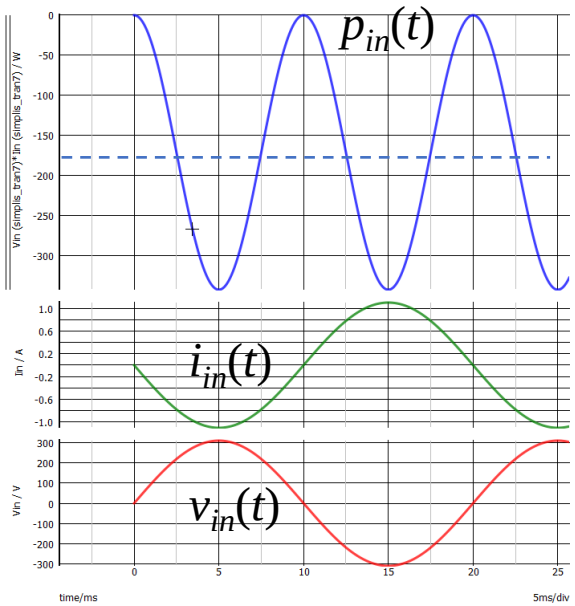
Absorbs

You have to sample with an ADC and a micro to compute the instantaneous power and determine its polarity. This video explains things well. The associated site is here.



This time, the right source has a voltage higher than the grid and the power is injected. This is the case when there is a surplus of solar power, for example. The current is now in phase reversal and the integral of the instantaneous power returns a negative value:

Name	Value
Mean	-171.05W



P_{avg} = -171 W

Injects

The annoying point with dimmer regulation, in my opinion, is the power factor which degrades with the control angle:

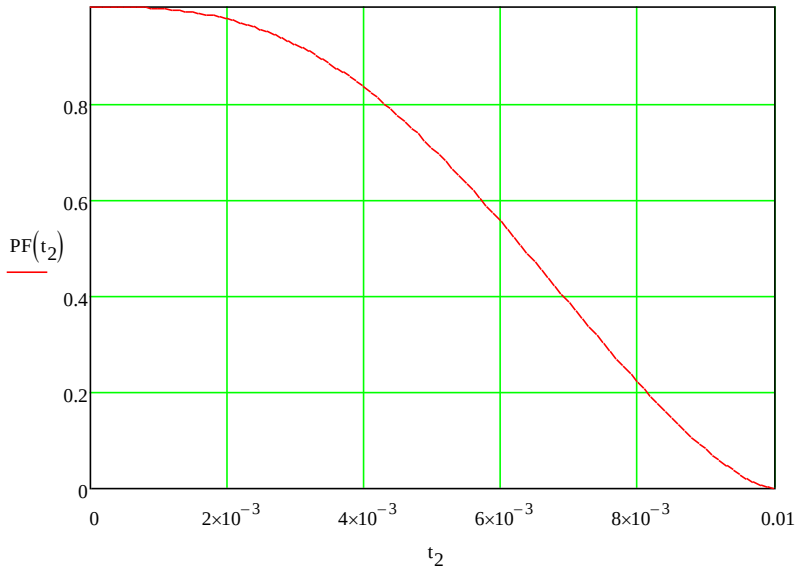
$$P_W(t_1) := \frac{(V_{rms}(t_1))^2}{R_L}$$ Rated power in W supplied to the load

$$P_{VA}(t_1) := \frac{V_p}{\sqrt{2}} \cdot I_{rms}(t_1)$$ Apparent input power, Vin_rms x Iin_rms

$$PF(t_1) := \frac{P_W(t_1)}{P_{VA}(t_1)}$$ Power factor

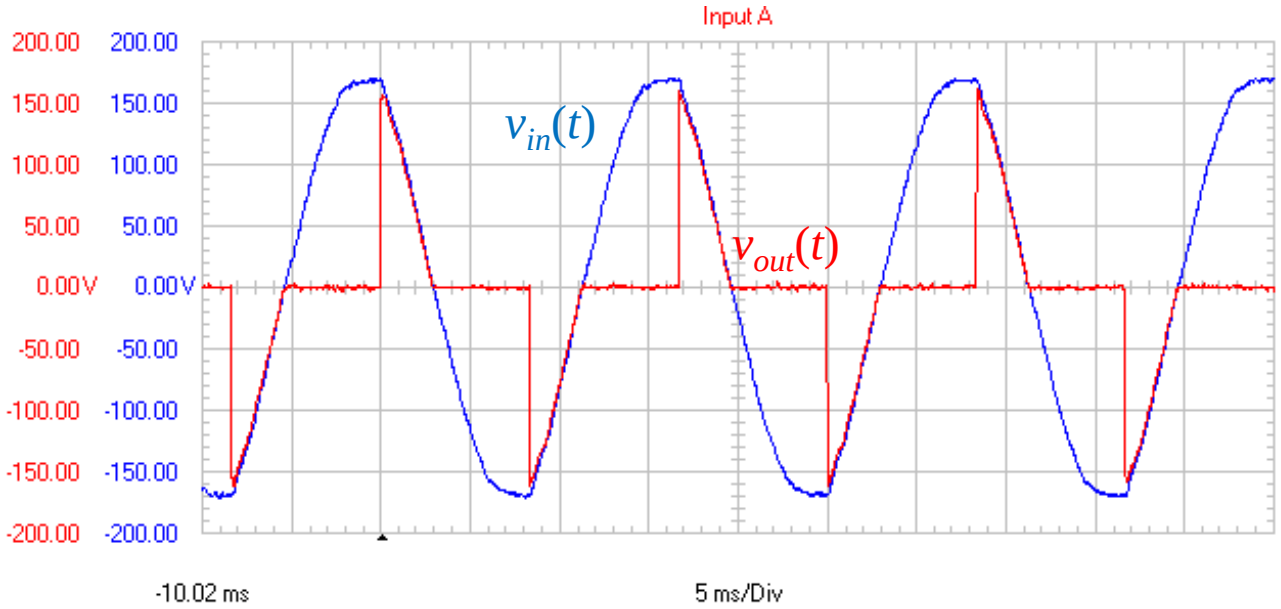
$$PF(t_1) = 0.92$$

1 = pure resistance

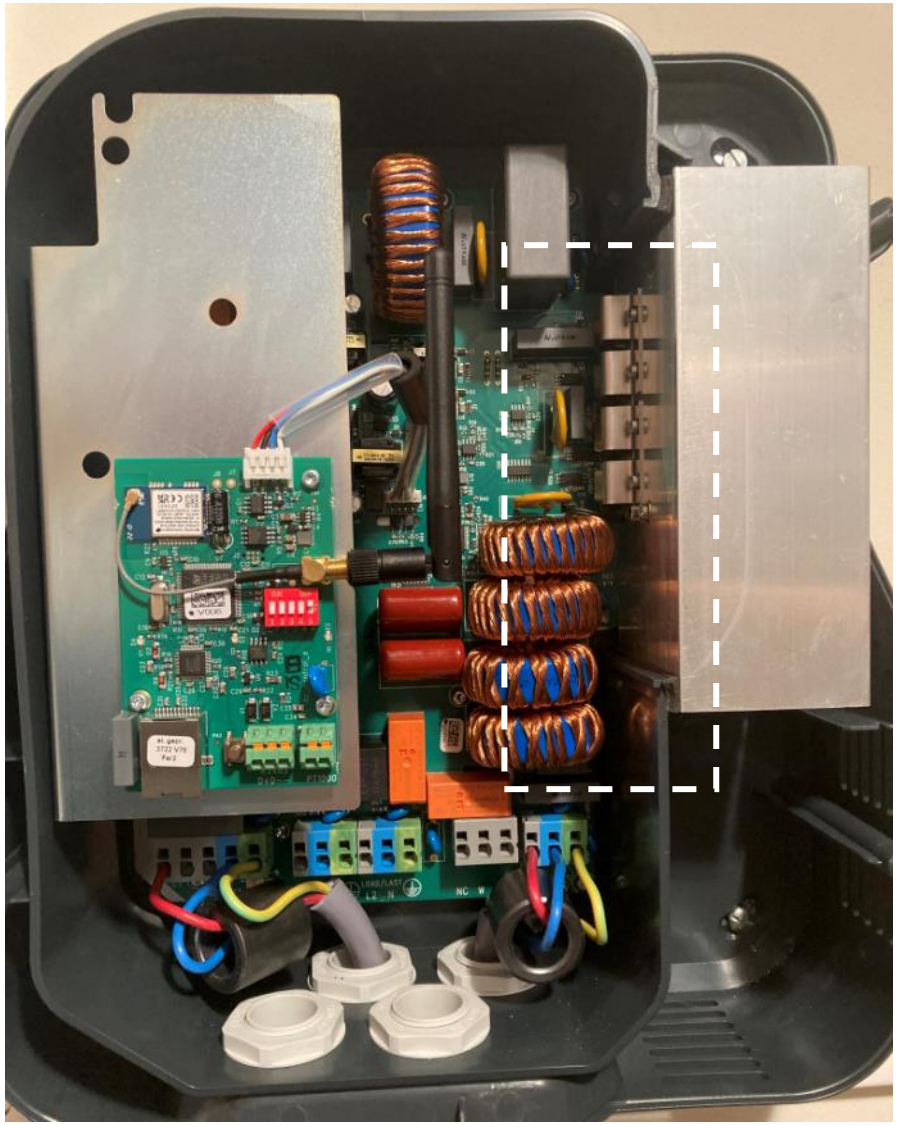


Power factor versus operating delay

For a triac conducting over the entire cycle, the load seen from the network is purely resistive. Then, when the conduction time of the triac decreases, by lowering the transmitted power, the current distortion increases and the apparent power also goes up, naturally degrading the power factor. This is the typical waveform obtained with these devices. Link here.



The solution of an ac-ac step-down converter or ac-ac buck converter seems to be the one chosen by Fronius. I did not have access to the schematic diagram but the presence of four TO247 packages could confirm this approach (with IGBTs or SiCs):



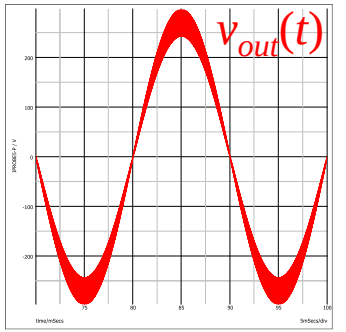
This 2006 article by Sam Ben-Yaakov describes the structure for a bidirectional implementation, like a classic ac transformer. The advantages and disadvantages of this ac-ac step-down approach are:

- ✓ Excellent performance across the power range
- ✓ Sinusoidal current drawn therefore power factor close to 1
- ✓ High frequency switching with small inductors

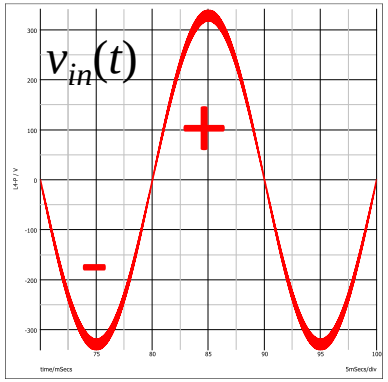
- ❖ Difficulty of implementation with a high-side control
- ❖ Opto-isolated drivers required, bootstrap would not work properly
- ❖ High- and low-side dc-dc modules with very low parasitic capacitance required given the dV/dt of SiCs. These offer 15 pF of parasitic capacitance between primary and secondary.
- ❖ High-frequency ripple in the cable supplying the tank. It conveys a significant amount of electro-magnetic pollution
- ❖ Filter of the input voltage considering the switching noise

Here is the operating principle of an ac-ac buck converter:

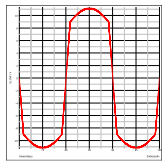
Output voltage



Input voltage

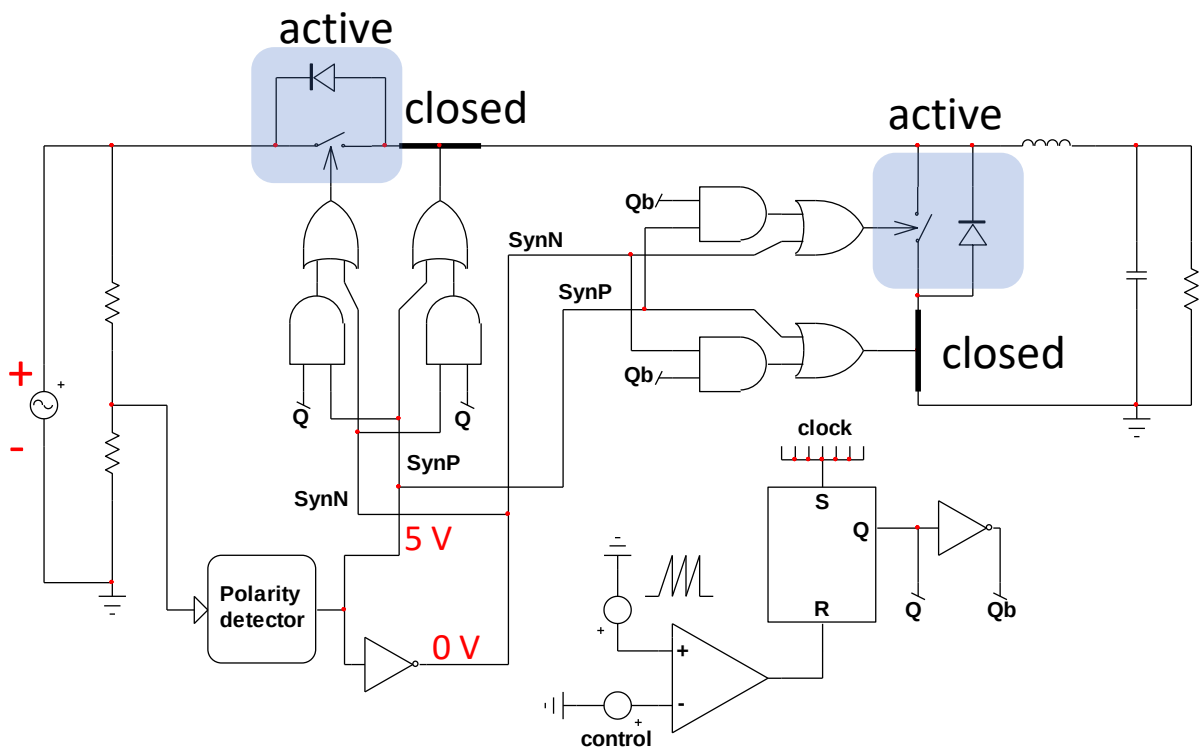


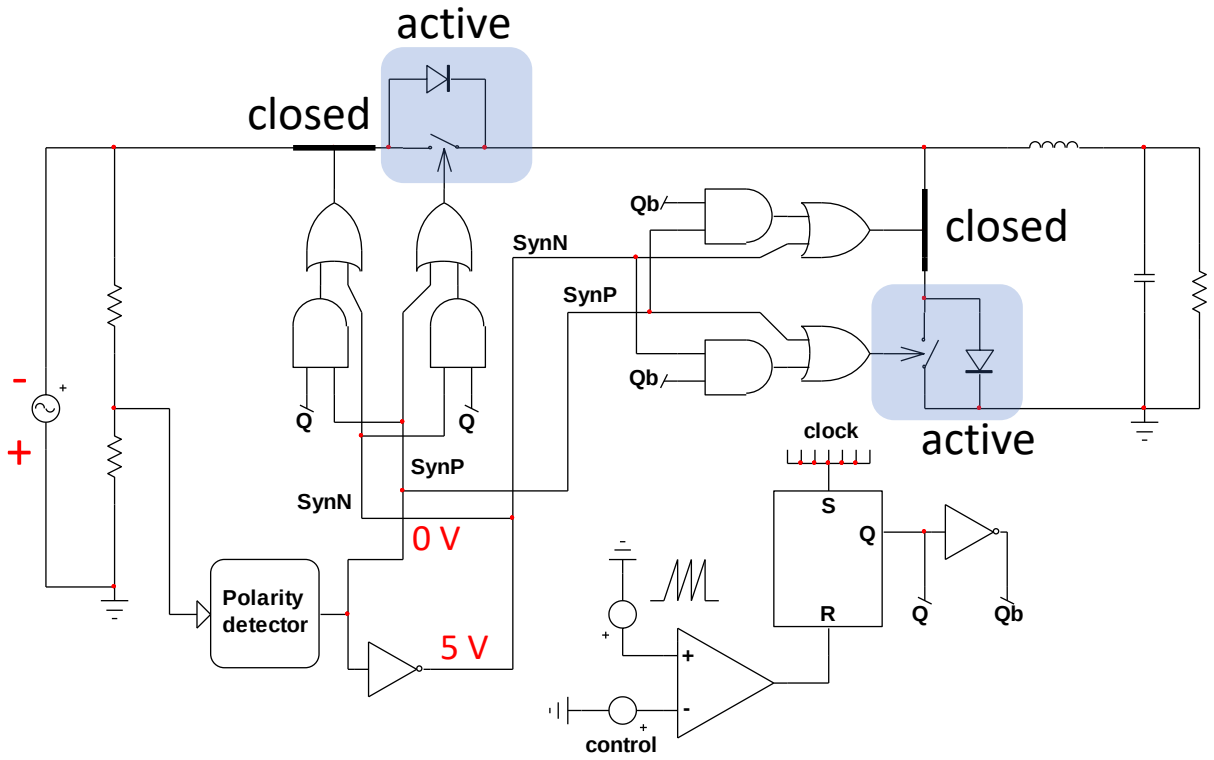
Clamped voltage



Cycle polarity

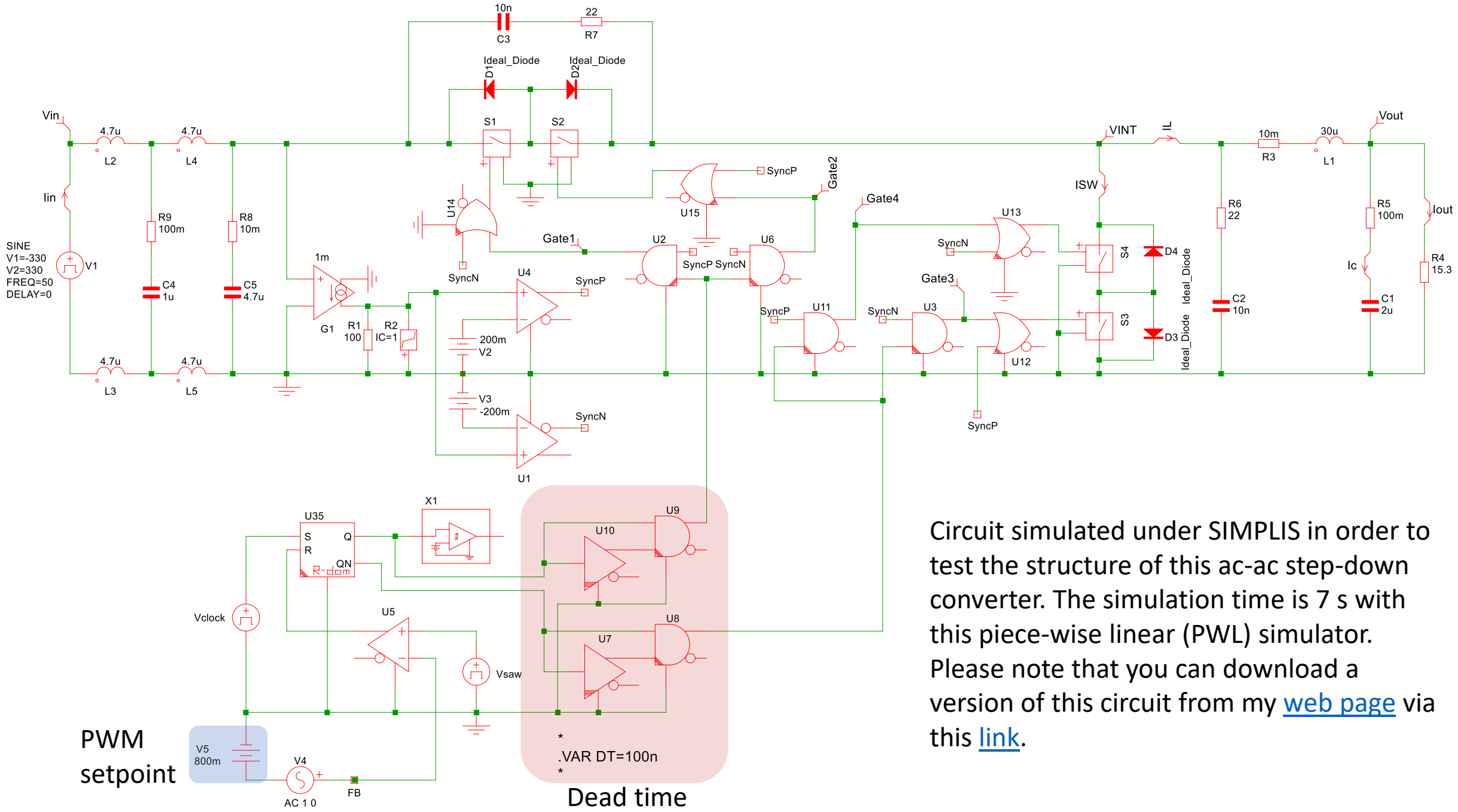
Pulse-width modulator





When the input voltage is positive with respect to ground, the circuit operates according to the principle of a classical buck with synchronous rectification. Two of the switches are permanently closed to ensure current flow. A dead time is inserted to control active switches and limit shoot-through currents. The control voltage adjusts the duty ratio and regulates the desired output voltage.

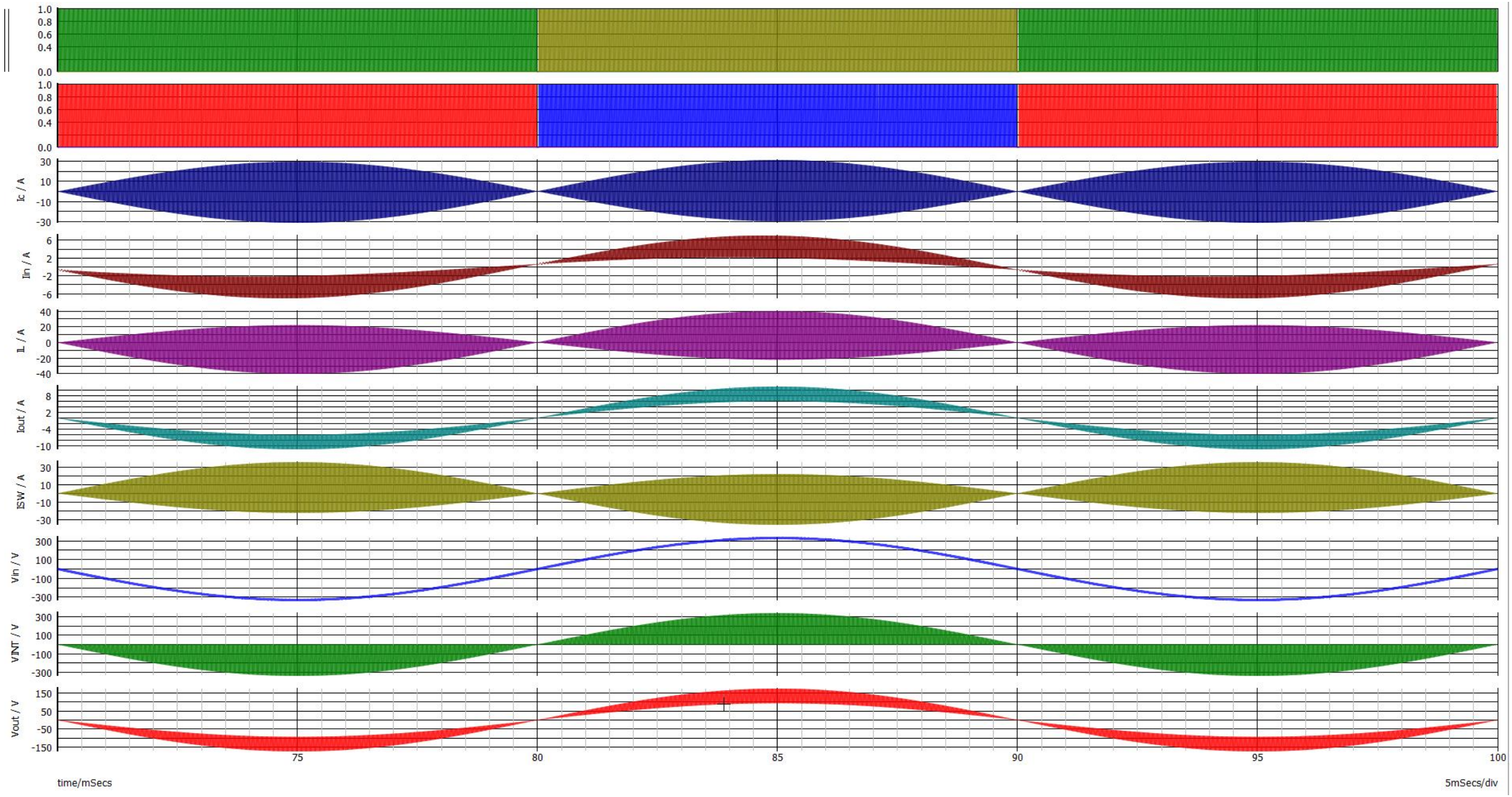
During negative cycle, previously-closed switches become active and those that were active are now closed. The current changes direction and the output voltage also goes negative in order to reconstruct the sinusoidal shape. A dead-time is inserted near 0-V crossing and it is possible that soft-start techniques are implemented as in a totem-pole type PFC.



PWM setpoint

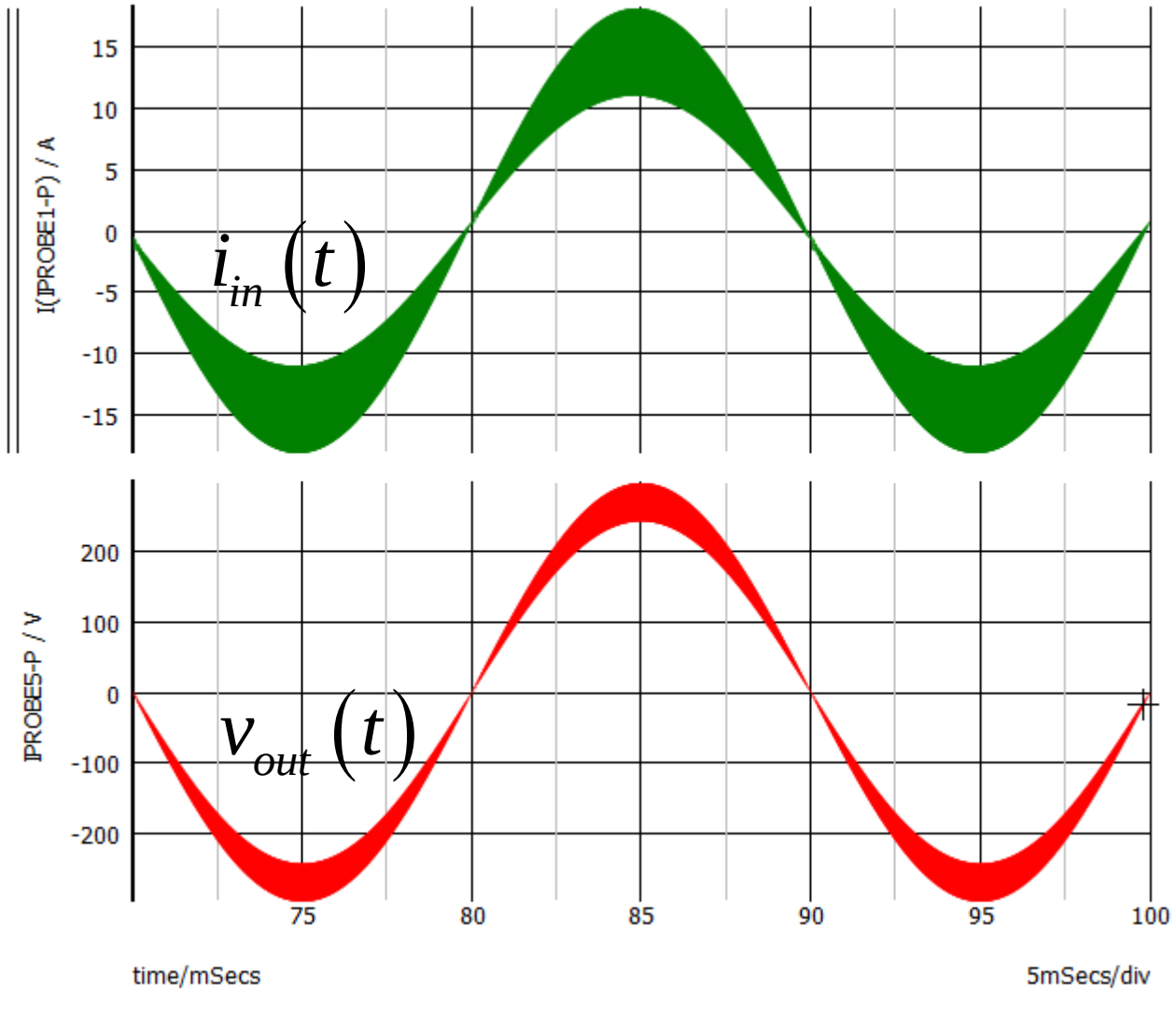
Dead time

Circuit simulated under SIMPLIS in order to test the structure of this ac-ac step-down converter. The simulation time is 7 s with this piece-wise linear (PWL) simulator. Please note that you can download a version of this circuit from my web page via this link.

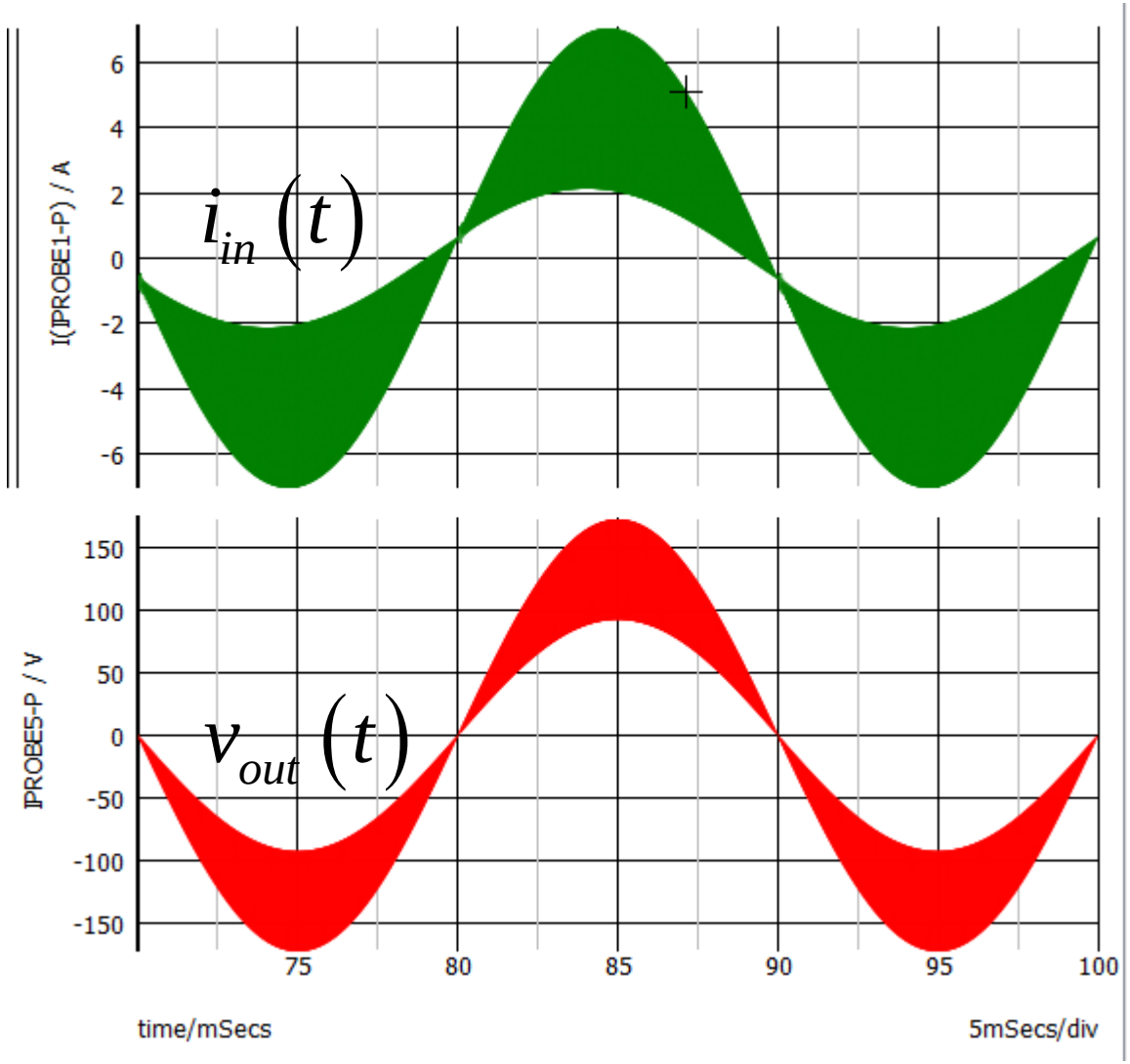


The waveforms are smooth and nicely sinusoidal. The output is in phase with the input and offers a very low distortion rate. This operating point programs the output at 106 V rms for an input at 230 V rms.

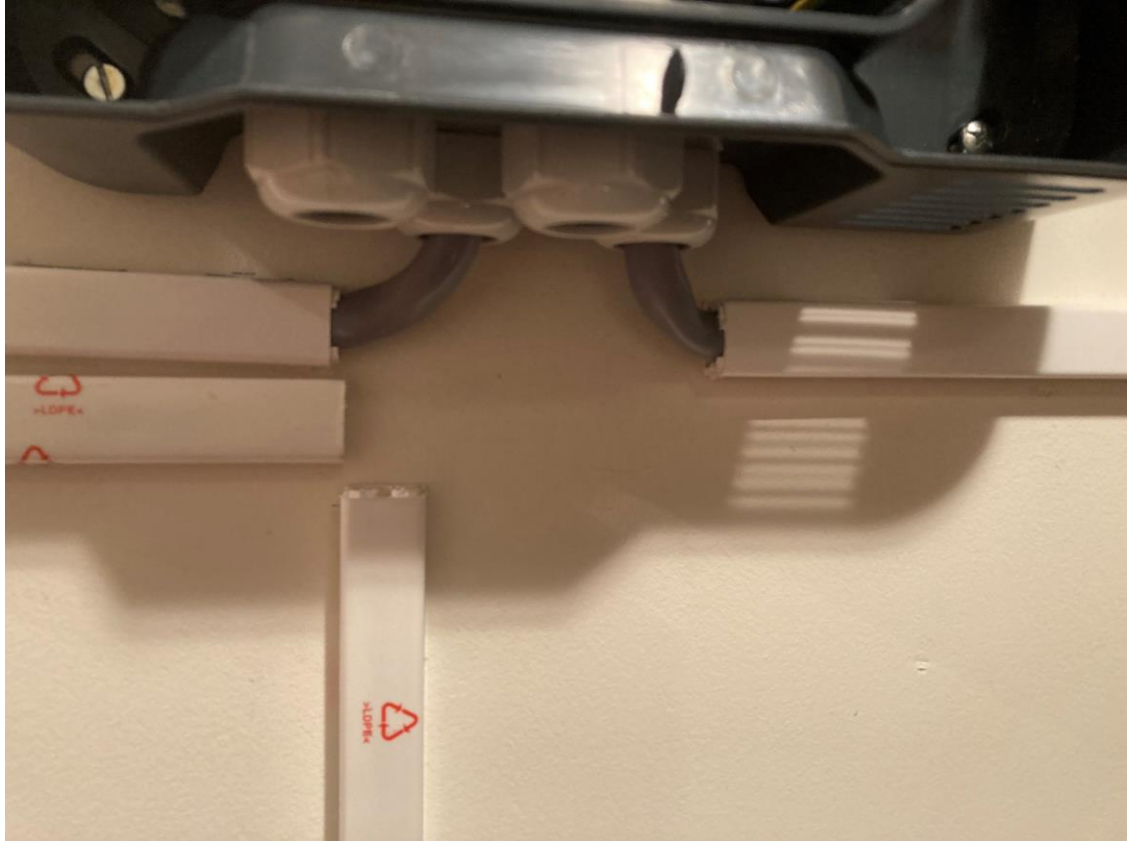
Here are two different operating points with the associated efficiencies: nominal power and one third of power.



V_{set} = 0.8 V → V_{out} = 188 V rms, I_{in} = 10.4 A rms → P_{out} = 2.3 kW, P_{in} = 2.39 kW, η = 96.2%

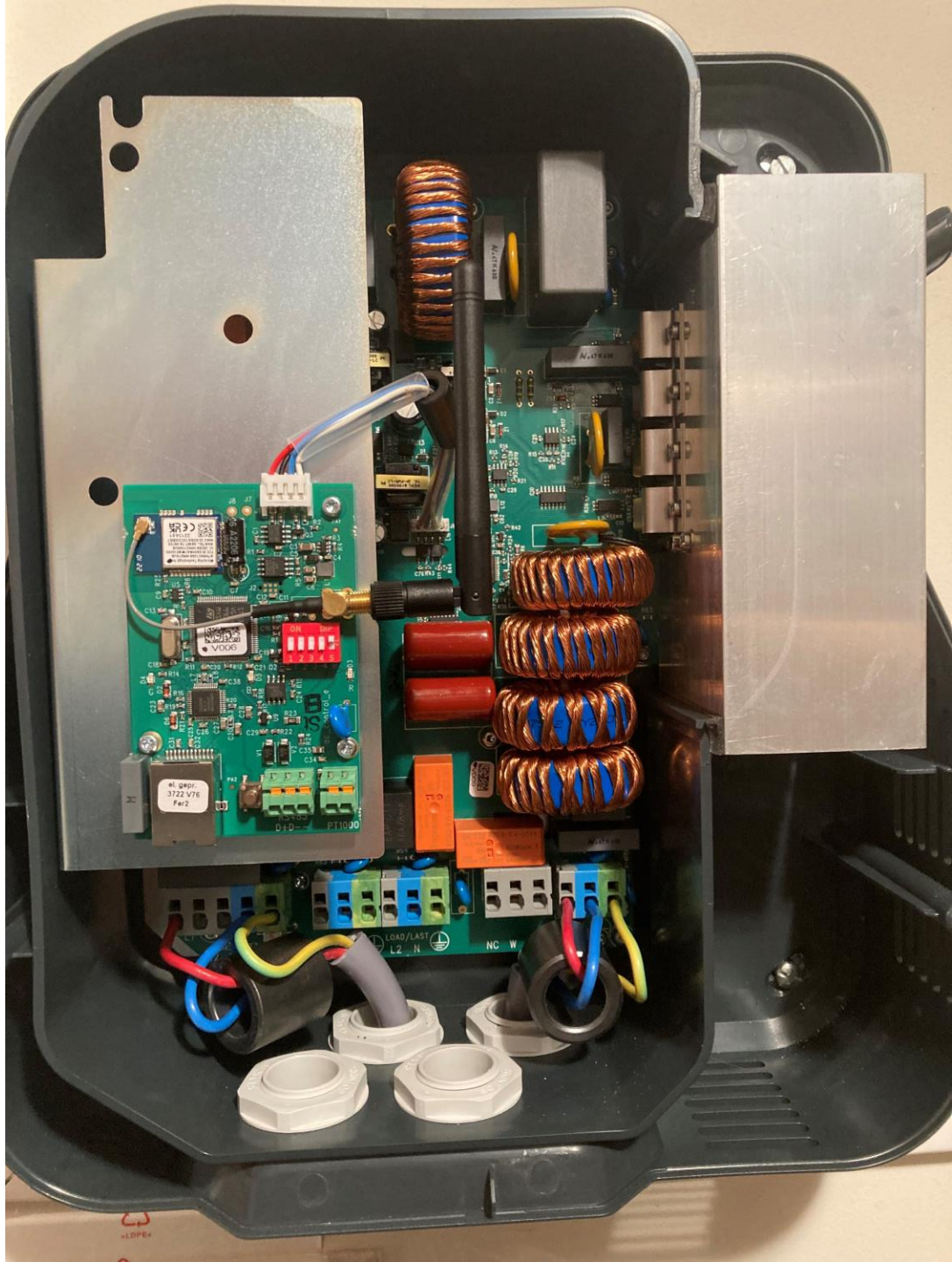


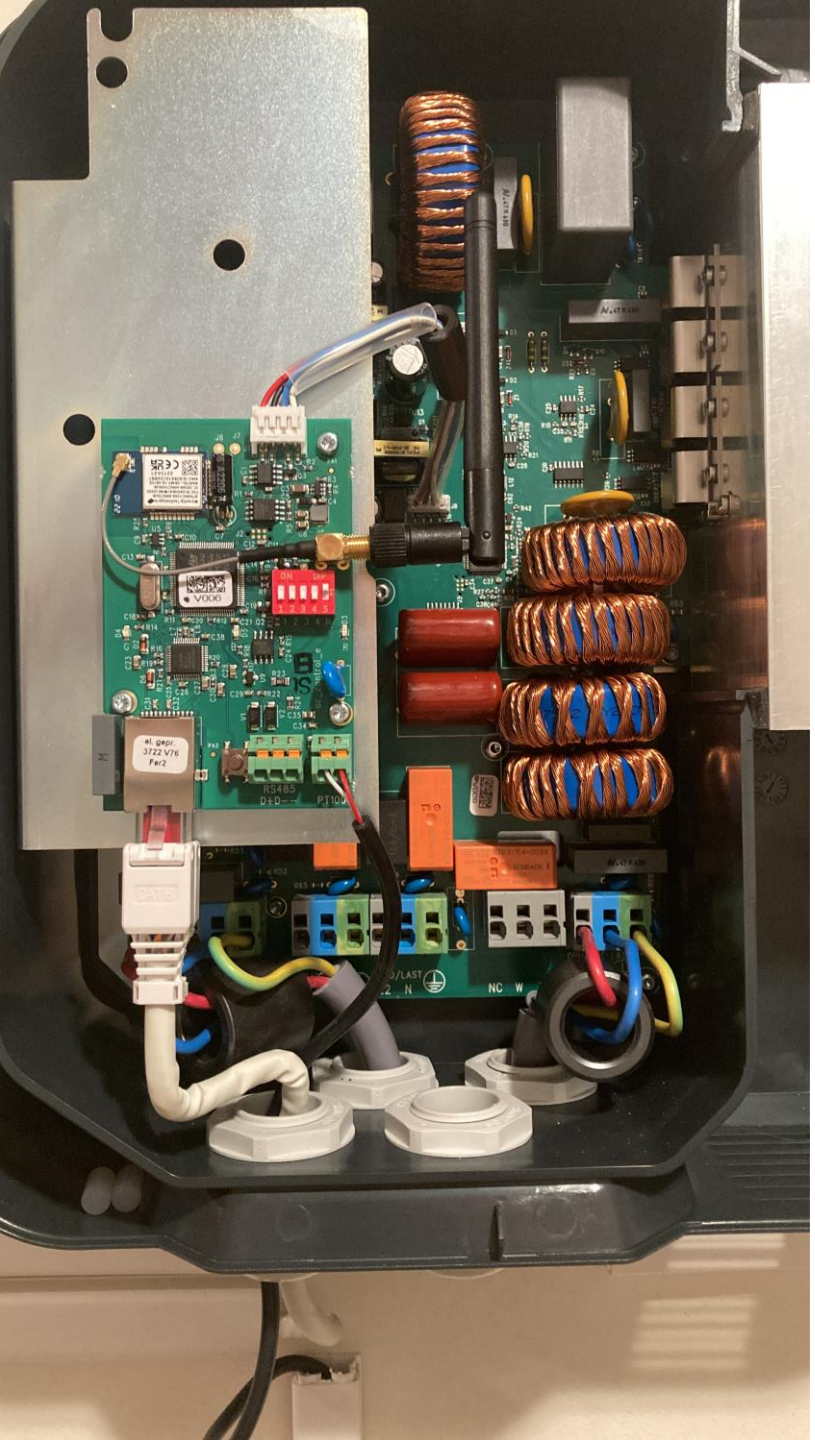
V_{set} = 0.4 V → V_{out} = 98 V rms, I_{in} = 3.28 A rms → P_{out} = 628 W, P_{in} = 754 W, η = 83.3%



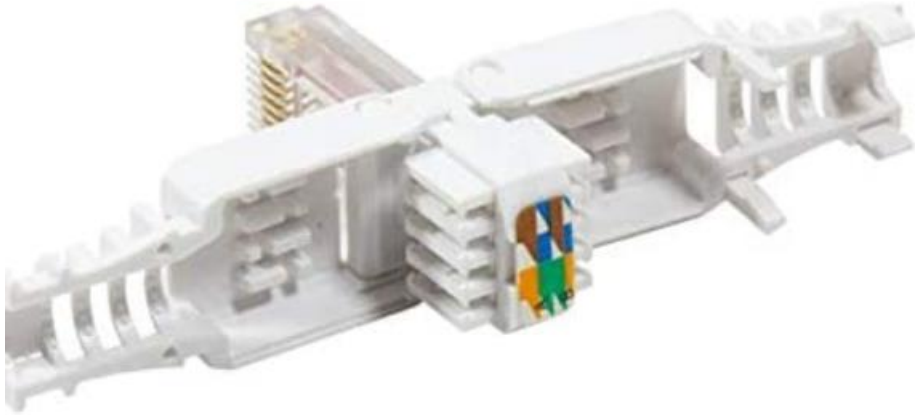
The Ohmpilot is placed on the wall and receives the electrical supply from the main electric switchboard (not backed up by the GEN24+), protected by a 30-mA differential breaker and a 16-A circuit breaker. The load planned for the Ohmpilot is 2 kW, i.e. a nominal current of 2k/230 = 8.7 A. I used 3 x 2.5 mm² rigid cable and protected it before entering the box. The Ethernet network is routed on the left side.

The output of the Ohmpilot is wired on the wall side and will be connected to the boiler resistance in a junction box. We can see the PT1000 probe which will measure the temperature of the tank. This will let the Ohmpilot ensure regulation automatically in solar mode but also at night, if external supply from the grid is necessary to bring the temperature up (no sunny day before).



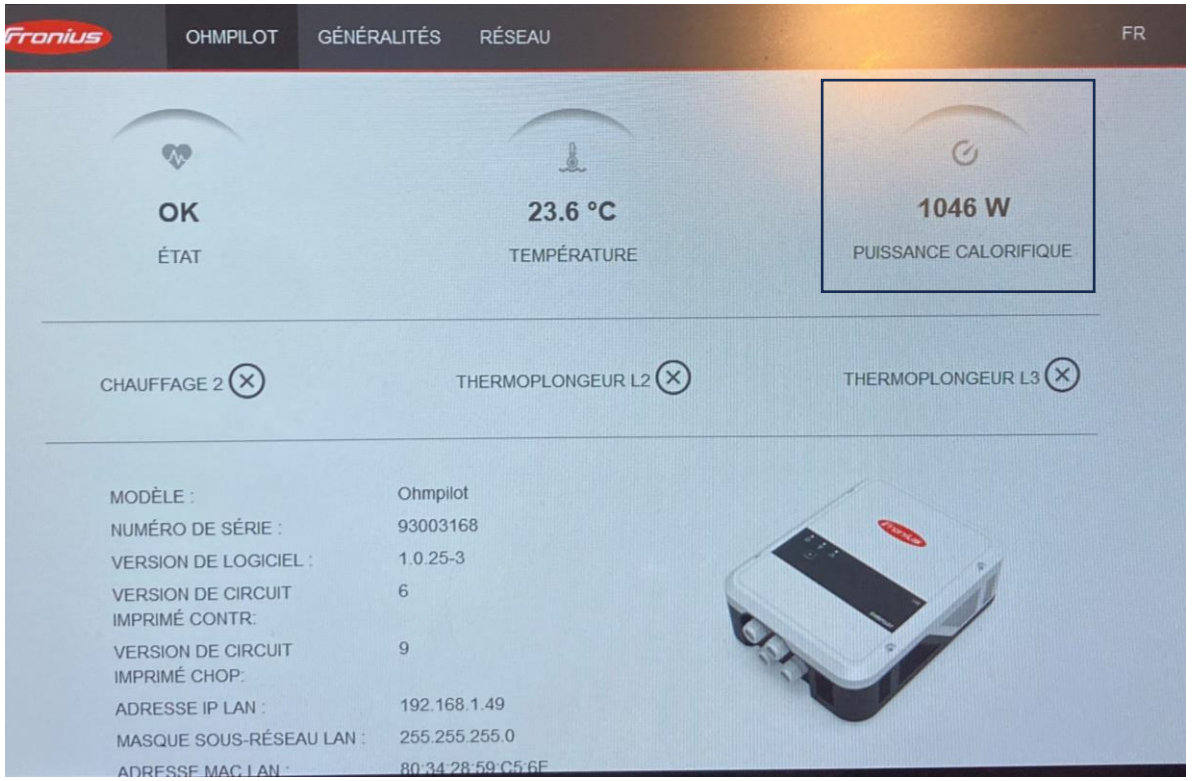


The Ethernet cable is a CAT6F/UTP 4 P but is very rigid and must be shaped well before inserting it into the RJ45 connector on the board. Otherwise, it can damage its connections to the PCB. In case I had to do it again, I would take a category below, shielded but more flexible like one of those described here. The RJ45 connectors are assembled without tools like those on the right. They are practical but require a minimum of dexterity and a burst of swearing is almost impossible to avoid while assembling them :)



I took shielded cables but there is no metal connection/enclosure to connect the screen to these connectors so no grounding of the shield but it works fine.

The first start-up is done using a 2-kW heater equipped with a fan. This latter is turned off and only the resistance remains which is measured at 26.5 Ω or 1,996 kW at 230 V.



A secure temporary assembly via a 16-A female socket is made to easily connect the heater.

There is sunshine and the house absorbs little power at this time. The surplus is 1.046 kW (top right) and the voltage is adjusted to the heater. The temperature is that of the ambient measured by the PT1000 in the air. It will be that of water later on.

P = 0

P = 667 W

P = 804 W

P = 1.65 kW

I chose this OSO boiler, made in Norway with a stainless steel tank and soapstone resistance. Its diameter is constant at 58 cm for the 150-200 and 300 liter models. I took a 300-liter type, it costs € 1031. I ordered it from France Solaire Chauffage and it was delivered quickly.

Avantages du ballon inox avec résistance stéatite :

- Cuve Inox AISI 444
- Résistance stéatite 2kW 230 V
- Soupape de sécurité 9 bar prémontée / vanne de vidange (Image point A)
- Vanne mélangeuse manuelle prémontée
- Doigt de gant pour sonde prémontée - Ø8 mm
- Connexions 1/2" pour eau froide et eau chaude
- Câble et fiche électrique prémontés
- Thermostat de contact intelligent réglable de 40°C à 70°C - température de réglage 65°C
- Pieds réglables inclus
- Isolation en PU rigide

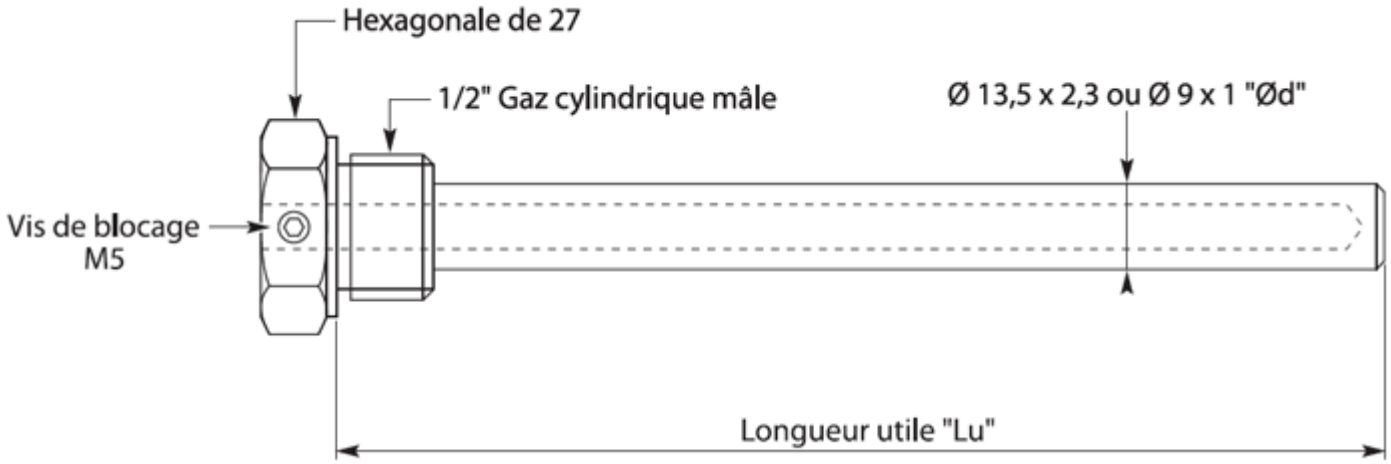
Non, c'est erroné, pas de doigt de gant mais une entrée en ½"

According to the seller, it is equipped with a thermowell into which I can slide the PT1000 probe. This is wrong, there is none. So I'm going to order a thermowell and slide it into the 1/2" hot water connection.

I have added a small volt-meter with needle (it does not care about HF noise) to check power.

This ½" threaded connector should allow me to insert a 60 cm-long thermowell in order to measure the temperature correctly, almost in the middle of the boiler. Check carefully for the presence of this thermowell, otherwise no measurement of temperature is possible.

Here is the thermowell that I found and which should be suitable:



This is the DGV1209-590 reference which is 9 mm in diameter and is suitable for housing the probe. It is 60-cm long and will dive right into the heart of the boiler for the measurement.

DGV1209-590	9	600

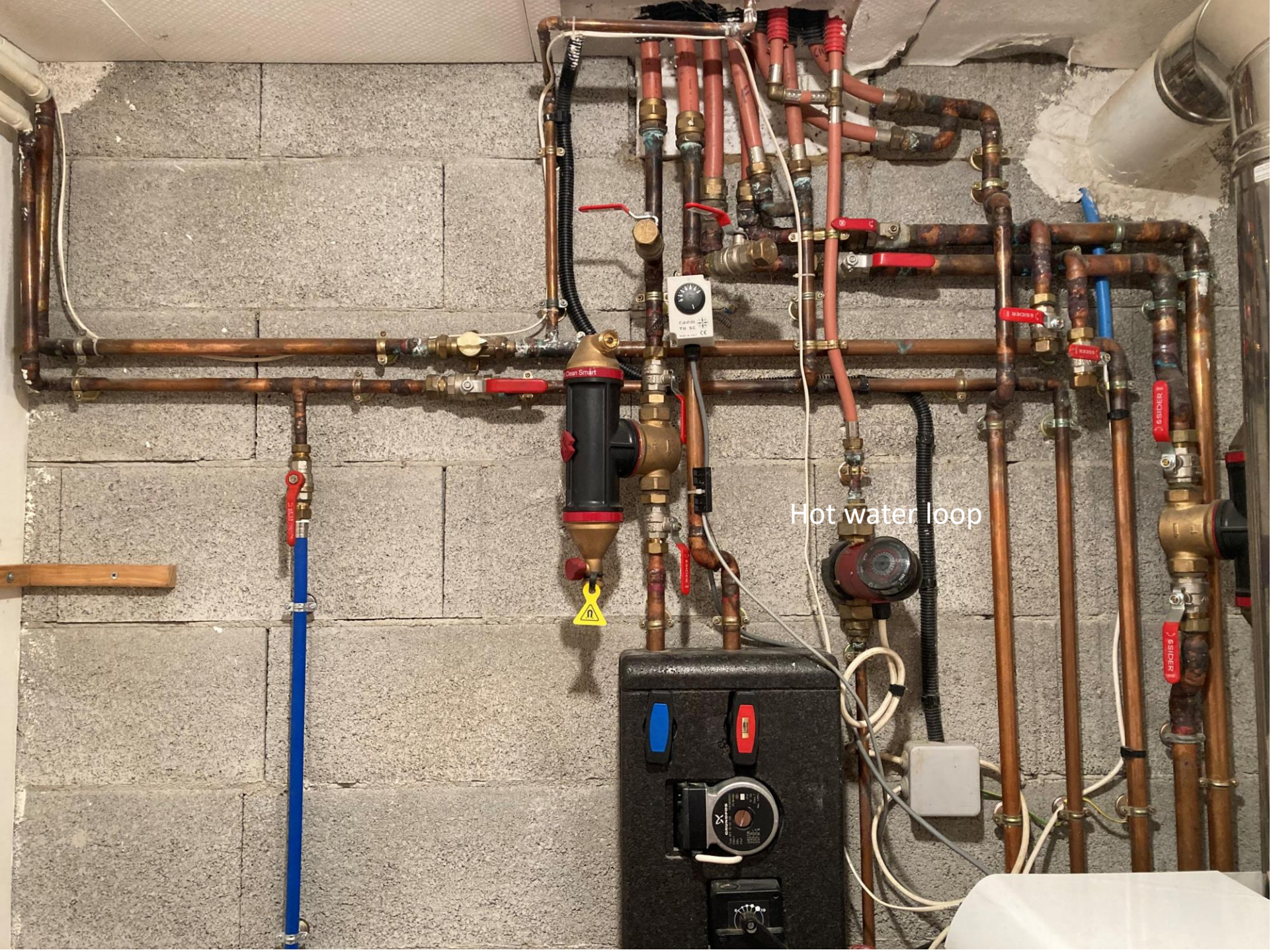
TOTAL NET H.T	Frais administratifs / Port	Taux TVA	TOTAL TVA	TOTAL TTC
45.09	0.00	20.00	9.02	54.11 EUR

ELEC SUD-OUEST
Bureaux et magasins :
13 Avenue de Larrieu
31100 Toulouse
elecsudouest@etn.fr
Tél : 05.34.61.57.57
Fax : 05.34.61.57.59

The thermowell has arrived and it is perfectly suited to insert the PT1000 probe. I was thinking of coating the probe with thermal grease but the plumber advises against it because these components can dry out and could potentially block the probe.

The thermowell will then be fitted with plumbing tow and firmly screwed to the ½” threaded connector.

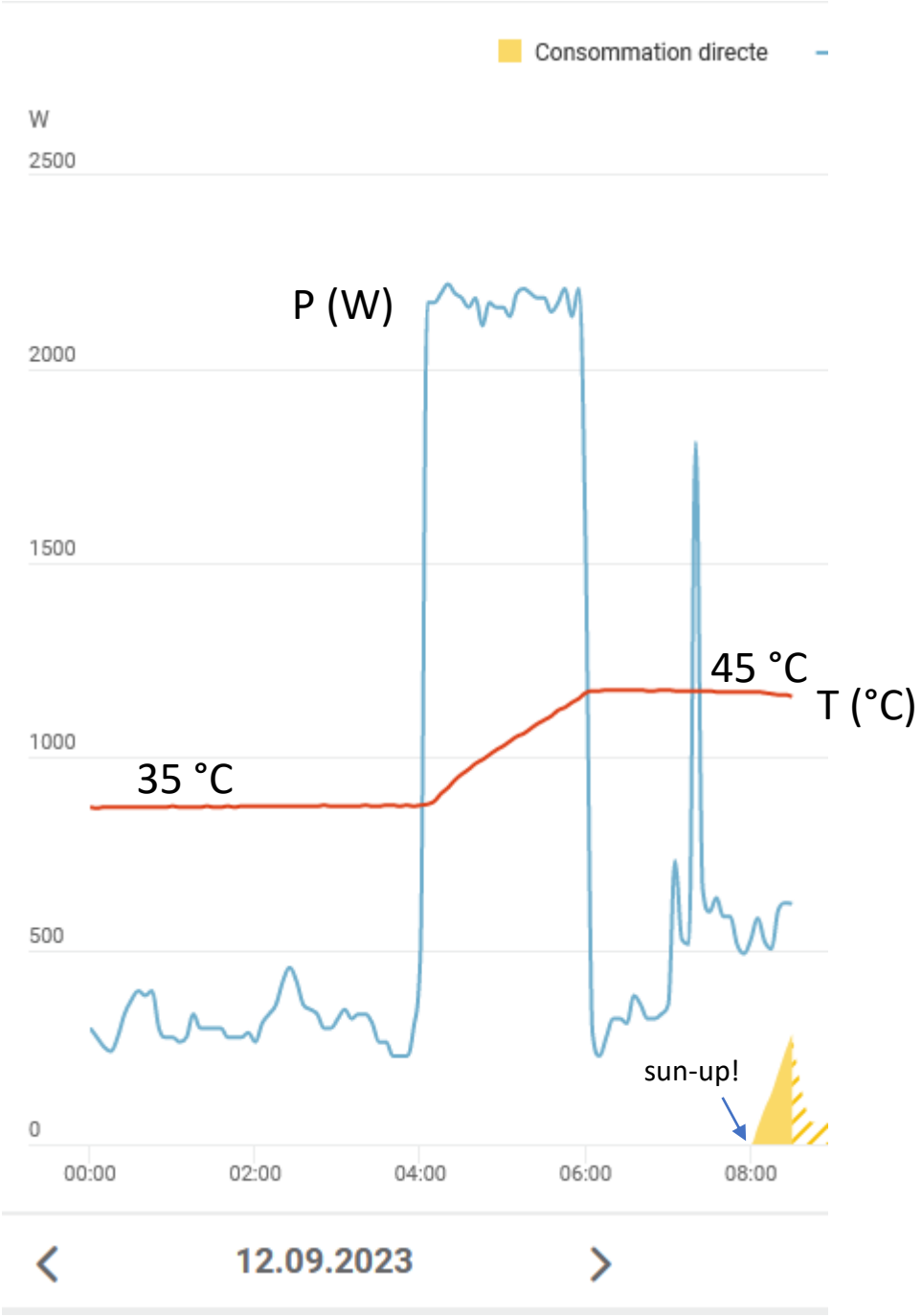
The thermostat allows you to adjust the temperature up to a maximum of 70 °C. I will set the maximum in the Ohmpilot at 60 °C in order to leave 10 degrees of margin.



The tank will be placed on the left, in series with the cold water entering the gas boiler. ¼-turn valves will allow me to operate exclusively on the tank in summer (boiler off) then to preheat the domestic water in winter. A hot water loop is already there and it must be included in the assembly.

The installation is completed and the boiler receives the excess solar energy. Unfortunately, given the very dense configuration of the existing pipes, it was not possible to connect the tanks in series as initially wanted. They are mounted in parallel and independent of each other: in summer, the electric tank will supply, alone, the circuit with domestic hot water and, in winter, it will give way to the gas boiler. Each time one or the other tank is restarted, it will be necessary to ensure a temporary rise in temperature greater than or equal to 60 °C in order to eliminate any harmful Legionella disease germs.

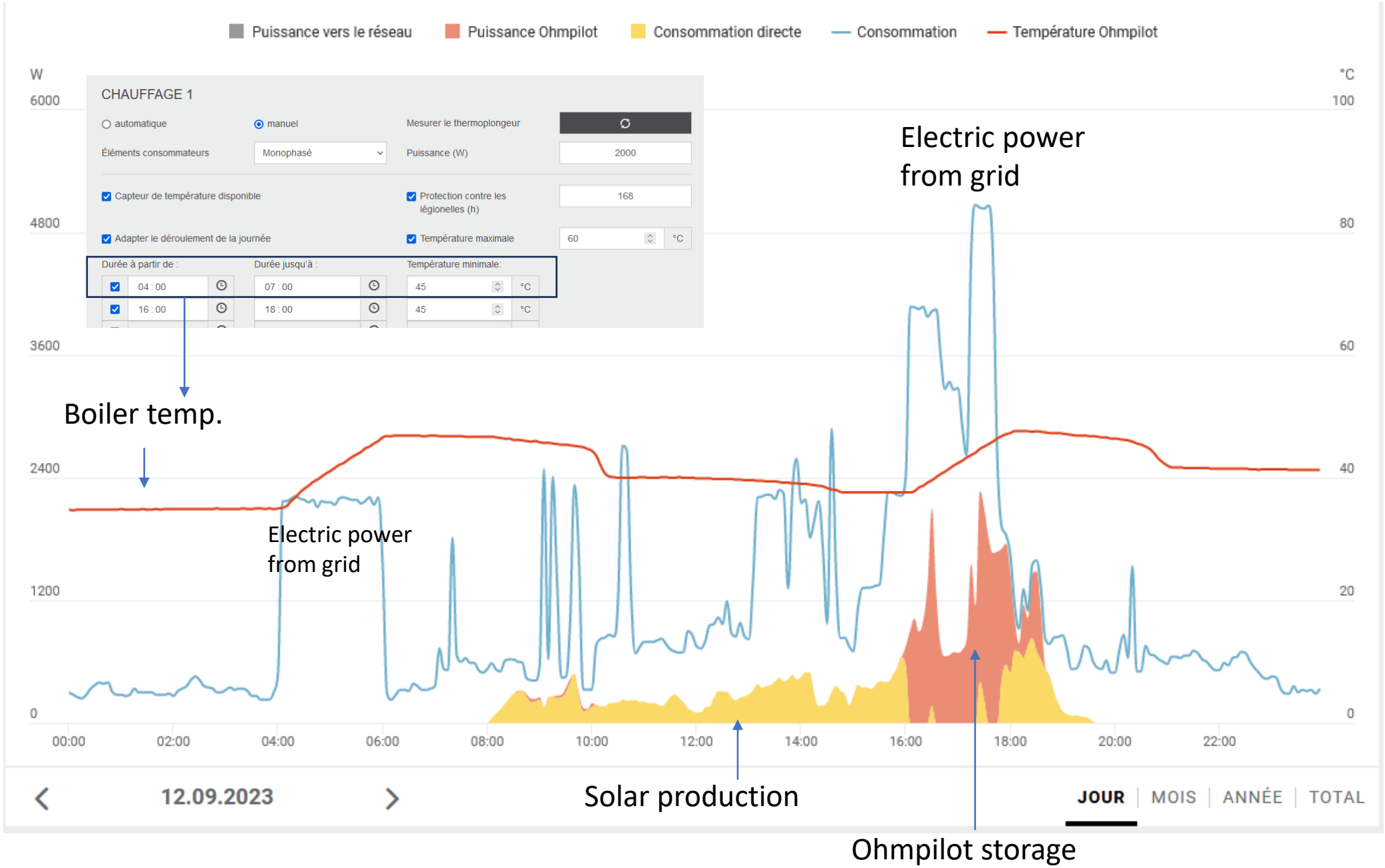
The PT1000 probe cable is guided via plastic gutters and the cover is placed on the top of the tank to hide the various electrical and hydraulic connections. It’s functional!



The Ohmpilot triggered as planned last night to raise the temperature to 45 °C. At 4 a.m. it was at 35 °C. The power being 2 kW, the setpoint was reached in 2 hours, representing an energy consumption of 4 kWh. What do calculations say?

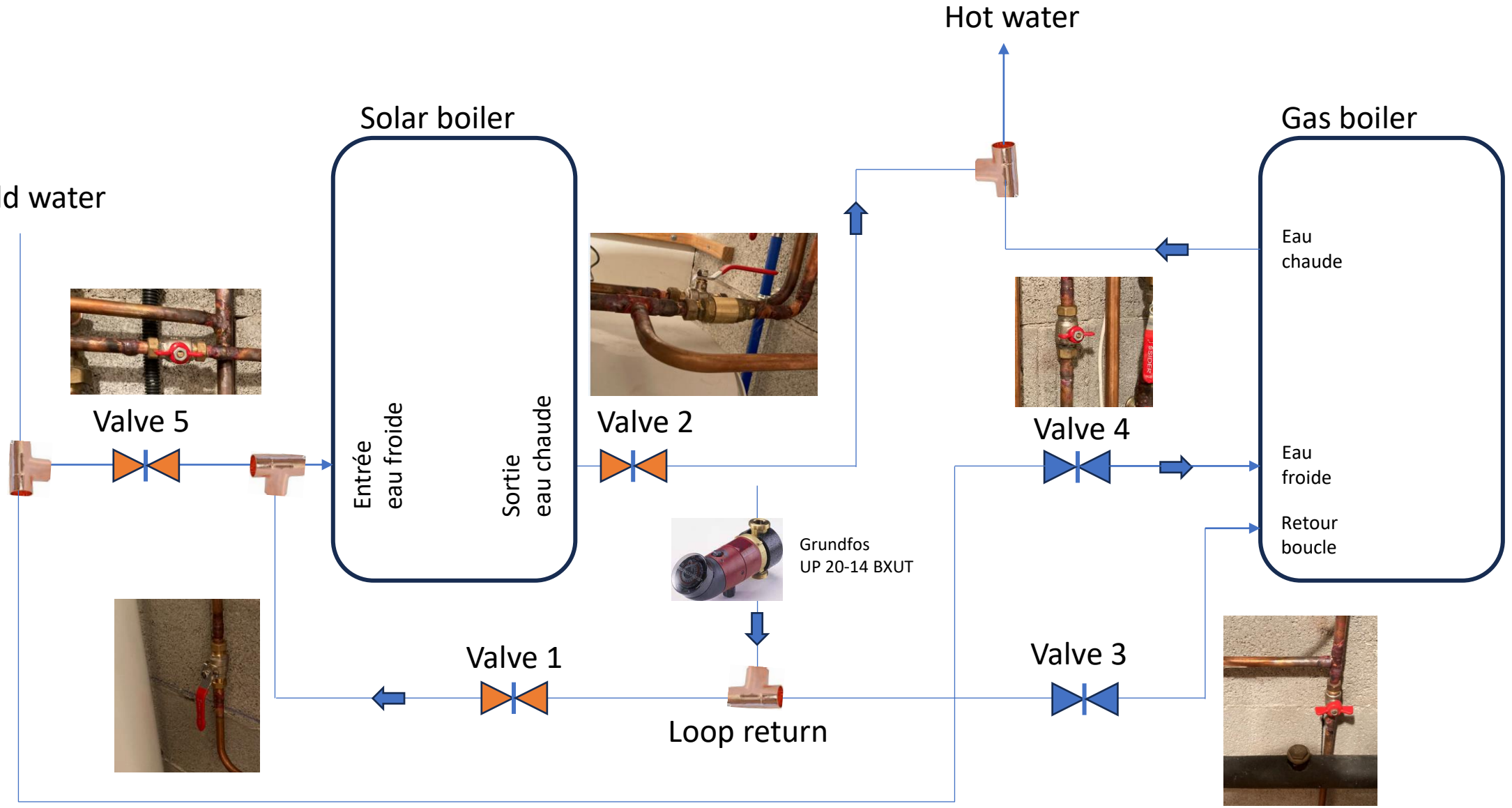
To raise a liter of water by 1 °C, 1,162 watt-hour of energy is required. Thus, to raise the temperature of the tank by 10 °C, considering the 300-liter volume, it will be necessary to produce: 1,162 x 300 x 10 ≈ 3.5 kWh, we are on target.

The series installation of the tanks, originally planned, would have allowed the solar boiler to pre-heat the water injected into the gas boiler in winter. The temperature of the injected water would have been naturally higher than that of the water distribution network (assuming a few watt hours of solar energy available) and energy would have been saved. Given the adopted configuration, I will leave the electric tank cut off from November to March and, then, in good weather, the tank will be put back into service by lowering the boiler's setpoint to 10 °C in order to keep the central heating but without hot water production through gas. As indicated previously, any return to service of the tank will be preceded by a temporary rise in temperature to 60-65 °C in order to eliminate all potential germs.



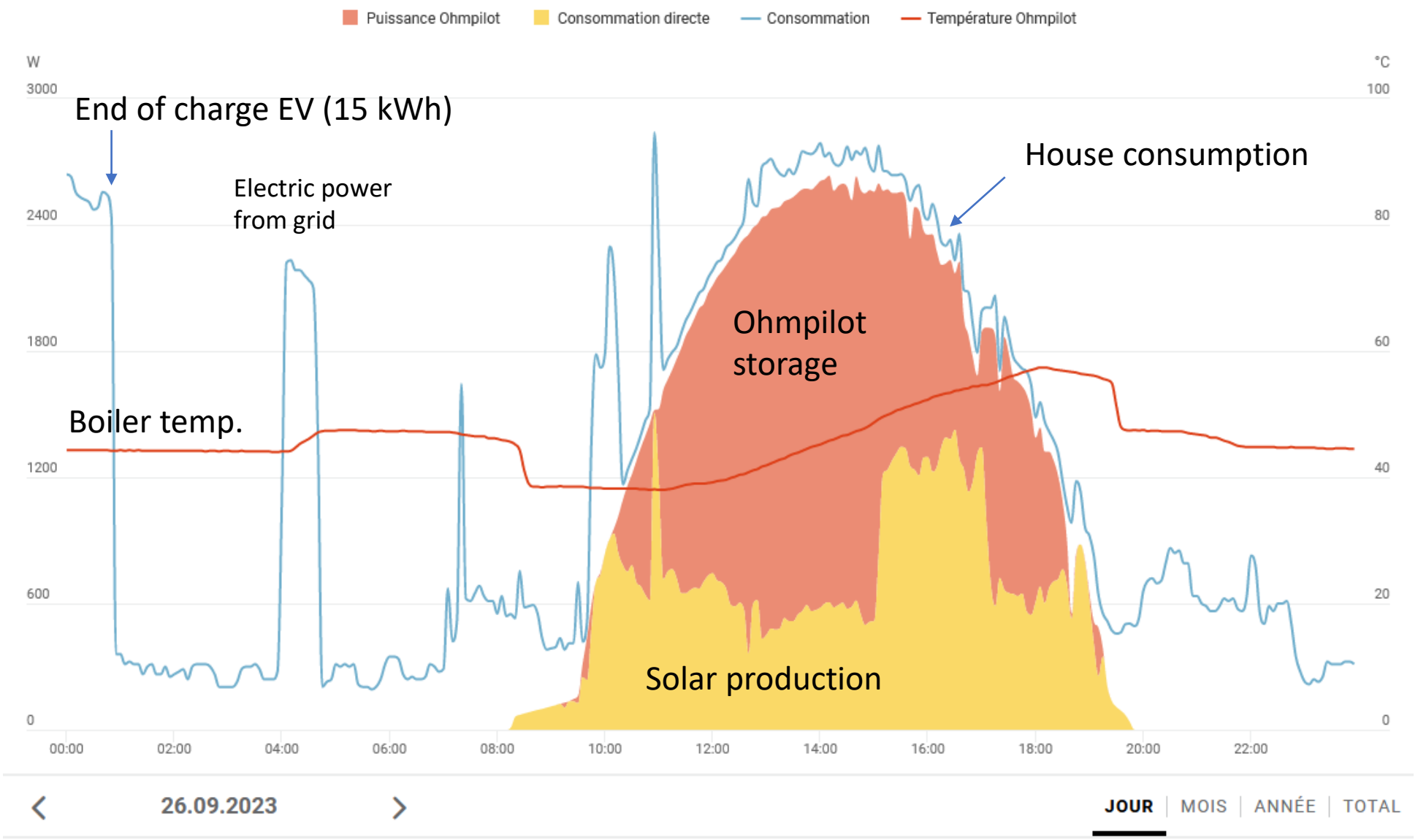
Summary of a lightly sunny day.

Final configuration:



Summer: valves 1, 2 & 5 open, valves 3 & 4 closed
Winter: valves 1, 2 & 5 closed, valves 3 & 4 open

Typical chart obtained with a sunny day, September 26th 2023



Electricity savings in September:
≈ 38% reduction in kWh

Ohmpilot started September 11th 2023
Gas boiler stopped September 13th.