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## **The first electric bus with an unlimited range**

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### **Summary**

Based on 25 years of experience in full electric vehicles (bus & trucks) PVI – Power Vehicle Innovation – designed Watt System. WATT system allows an automatic charge at every bus stop in only 10 seconds!

The original idea was patented in 2009 in order to build a full electric solution with similar performance as a diesel bus without any heavy roadworks.

WATT system is now a revolution because it is the solution for a bus with an unlimited range. And it is already in operation: Nice airport (France) has entered into the future with PVI since February 2015.

*Keywords: bus, conductive charger, EDLC (electric double-layer capacitor), electric vehicle, fast charge*

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### **1 Introduction**

Based in France and open to the world, we strongly believe that it is urgent now to go for a cleaner transportation to help our cities and their people breathe easier. That's the reason why we are developing for ten years full electric transport solutions adapted to cities: bus, trucks and fast charging system. Designed and assembled in France, our full electric vehicles are already in operation in nearly 40 French and European cities which trust us.

With WATT system, we are looking forward for an ambitious technology based on a full electric drivetrain for city bus networks. With this solution, a standard bus fitted with an electric motor will have an unlimited range thanks to quick charges at each stop in only 10 seconds (while passengers enter and exit).

It offers major technological advances to bus operators. Furthermore, this solution is easy to implement across existing bus lines and may be integrated into standard 12m city bus.

### **2 How does it work?**



At each stop, the bus automatically charges its supercapacitors in 10 seconds. The energy transfer is made between supercapacitors from the station to the supercapacitors of the bus at 400kW. The bus stores enough energy to reach the next stop and even more.

## 2.1 Why going for a supercapacitor city bus?

Today's bus market is asking a full electric solution with the same capacity of passengers as a diesel bus and without limit of range. A battery electric city bus with depot charging is able to provide a full electric solution but the capacity is usually downgraded and the range is limited. The concept of the WATT system is to reduce as much as possible the embedded energy storage system to increase the capacity of passengers and offer many charging points to unlimited range. The supercapacitors have the capability to charge and discharge very quickly. So that's why WATT system can realize energy transfer in station within only 10 seconds.

Table 1: Comparison between 3 types of charging

|                                 | Battery Bus (1) | Opportunity Charging (2) (3) |                            |
|---------------------------------|-----------------|------------------------------|----------------------------|
| Type of Charge                  | Depot charge    | Quick-charge at each station | Fast-charge at end of line |
| Energy Storage Technology       | Energy battery  | Supercapacitors              | Power battery              |
| Energy Storage Lifetime (4)     | 5 to 7 years    | 15 years                     | 8 to 10 years              |
| Passengers Capacity             | 70 to 80        | 90 to 100                    | 80 to 90                   |
| Flexibility of Operation (5)    | Very good       | Very good                    | Medium                     |
| Flexibility of the Bus Line (6) | Very good       | Medium                       | Good                       |
| Range                           | 180km           | Unlimited                    | Unlimited                  |
| Initial Investment (7)          | Low             | High                         | Medium                     |
| TCO (8)                         | Poor            | Good                         | Good                       |

## 3 Electric by PVI inside

Watt system includes a standard full electric bus and a charging station

- Supercapacitors offers an extra-long lifecycle more than 15 years, (9)
- High-power energy transfer from supercapacitors to supercapacitors is done through a DC/DC converter,
- Security is ensured by a 4-poles connection between bus & station,
- The electronics integration is compact with cooling plates to save volume and weight.

### 3.1 System architecture

The architecture of the system is described in the next figure. The bus is fitted with a lithium-ion (FePO<sub>4</sub>) battery pack and an EDLC pack. Each energy source is connected to the DC-Link through a DC to DC converter. The bus integrates also an AC to DC converter for the charging and the equalization of the battery pack at night. The station integrates also an EDLC pack and an AC to DC converter.

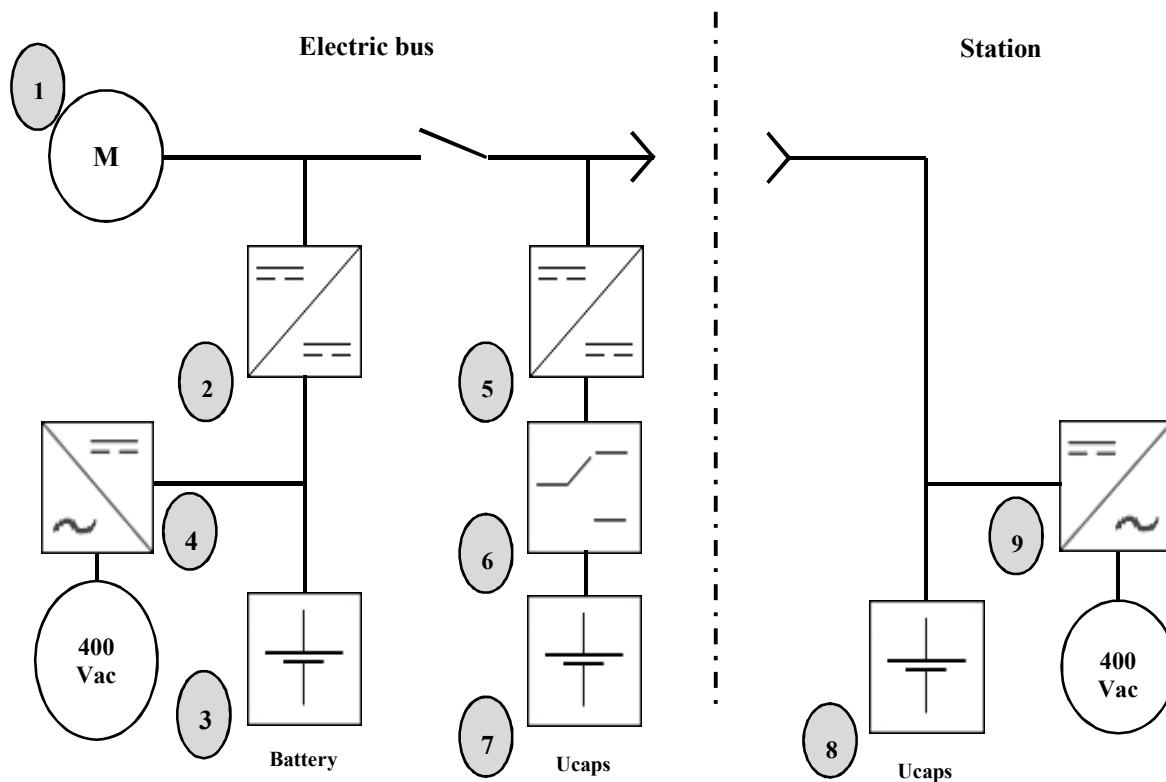


Figure 1: Electric architecture of the WATT system

#### Legend:

1. Auxiliaries components or consumers : drive motor, air compressor, power steering, air conditioning compressor and low-voltage equipment (24 vdc)
2. DC to DC converter for battery management
3. Battery pack of the bus
4. AC to DC converter, or charger, for battery pack of the bus
5. DC to DC converter for supercapacitors management
6. Configuration of supercapacitors
7. EDLC pack of the bus
8. EDLC pack of the station
9. AC to DC converter, or charger for supercapacitors of the station

### 3.2 Power requirements

The consumers (see 1 in fig. 1) are operating at a certain voltage range and are requiring electric power. Their characteristics are:

|                                  |                                                                                      |
|----------------------------------|--------------------------------------------------------------------------------------|
| <b>Voltage range</b>             | 500 to 800 Vdc                                                                       |
| <b>Drive motor maximum power</b> | 120 kW                                                                               |
| <b>Auxiliaries maximum power</b> | 18 kW for air compressor, power steering, air conditioning and low-voltage equipment |

### 3.3 About the bus



The bus is fitted with lithium-ion batteries and supercapacitors.

The drive power is supplied by both energy storages.

The overall capacity is 100 passengers.

WATT system has been designed to fit in any standard 12 meter city bus. It can be applied on new buses but also to retrofit old buses. It doesn't need a special platform so, from the customer point of view, the body of the bus is the same as a diesel one.

#### 3.3.1 Supercapacitors pack

The pack of supercapacitors is composed by 48 customized modules of 48.6 Vdc from Maxwell Technologies. They are physically integrated at the back of the bus, where the original diesel engine was fitted, according to the layout of the figure on the side. The modules are electrically connected in series and parallel according to following pattern:

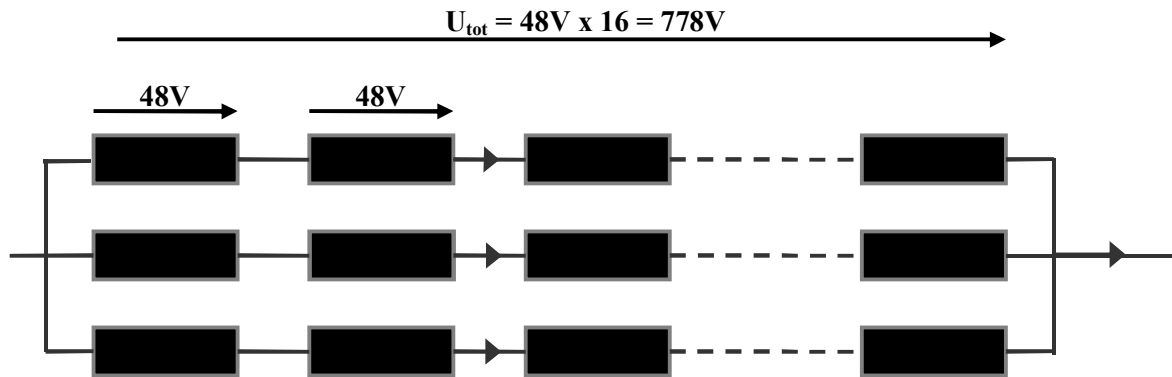


Figure 2 : Electrical configuration of EDLC pack in the bus

Characteristics of one supercapacitor's module:

1. Type : Maxwell BMOD0165 - 18 cells of 2.7V / 3 000F
2. Capacity : 165 F
3. Internal resistance : 6.3 mΩ
4. Nominal voltage : 48Vdc

Characteristics of the supercapacitor's pack:

5. Maximum voltage: 770 Vdc, or 2.67 Vdc per cell
6. Minimum voltage: 580 Vdc because of the working voltage of the driveline
7. Equivalent capacity: 30.94 F
8. Usable energy :

$$\mathcal{E}_{usable} = \frac{1}{2} \times C_{eq} \times (V_{max}^2 - V_{min}^2) = 4 \times 10^6$$

With:

$\mathcal{E}_{usable}$ : Usable energy, in Joules

$C_{eq}$ : Equivalent capacity of the pack, in Farads

$V_{max}$ : Maximum voltage of the pack, in Volts

$V_{min}$ : Minimum voltage of the pack, in Volts

### 3.3.2 Lithium-ion Battery

The primary function of the battery pack is to allow the deadhead trips from the garage to the bus line and allow the return trip even in case of failure. As a secondary function it gives flexibility to the system by allowing the driver to miss some charging station during the service.

The battery pack is composed by 30 individual modules from Valence Technology. They are installed on the roof of the bus. Each module is 19.2 Vdc for a capacity of 69 Ah, so the total embedded energy is 42.4 kWh. The modules are electrically connected in series as described in the next figure:

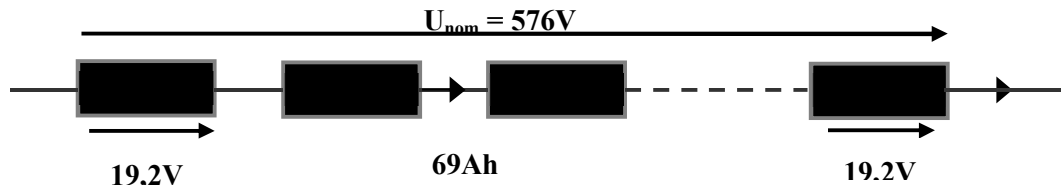


Figure 3 : Electrical configuration of lithium-ion battery pack in the bus

Characteristics of the battery pack:

1. Nominal voltage: 576 Vdc
2. Maximum voltage: 657 Vdc, at the end of charge
3. Minimum voltage: 450 Vdc, cut-off voltage
4. Nominal capacity: 69 Ah, at C/5, 23°C
5. Nominal energy: 39.7 kWh at 100% DOD  
31.8 kWh at 80% DOD
6. Charging current / power: 120A / 69.1kW, continuous load  
200A / 115.2kW, peak load (30s)

The battery is not able to provide constantly enough power for the drive motor and the auxiliaries. Because of that lack of power, PVI designed a specific strategy of power and energy management between the EDLC pack and the battery pack.

### 3.4 About the charging station



Charging stations includes also supercapacitors. They are completely integrated at each bus stop.



The station is powered by the low voltage city grid to charge the integrated supercapacitors before the bus arrives.

- Iron structure and aluminum casing to protect electronics in case of crash, fire and vandalism,
- Connection to the grid from 9 to 36kW adaptable to bus frequency,
- Integrated charger to slowly fill-up the supercapacitors,
- Smart charging and discharging management to improve supercapacitors lifecycle.

The pack of supercapacitors is composed by 28 standard modules of each 54 Vdc from Batscap. The modules are electrically connected in series and parallel according to following pattern:

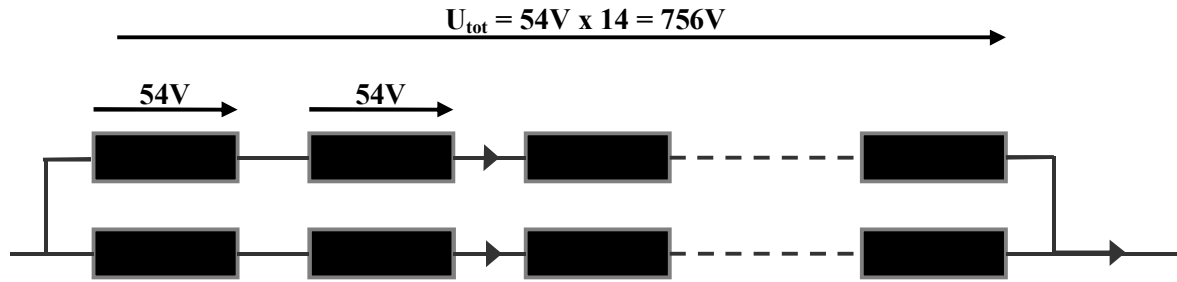


Figure 4: Electrical configuration of lithium-ion battery pack in the station

Characteristics of one supercapacitor's module:

1. Type : Batscap M54V150F - 20 cells of 2.7V / 3 000F
2. Capacity : 150 F
3. DC series resistance (25°C, 125A) : 4.5 mΩ
4. Nominal voltage : 54Vdc

Characteristics of the supercapacitor's pack:

5. Maximum voltage: 756 Vdc, or 2.7 Vdc per cell
6. Minimum voltage: 450 Vdc because of the characteristics of the power electronic
7. Equivalent capacity: 21.43 F
8. Usable energy :

$$\mathcal{E}_{usable} = \frac{1}{2} \times C_{eq} \times (V_{max}^2 - V_{min}^2) = 3.95 \times 10^6$$

With:

$\mathcal{E}_{usable}$ : Usable energy, in Joules

$C_{eq}$  : Equivalent capacity of the pack, in Farads

$V_{max}$  : Maximum voltage of the pack, in Volts

$V_{min}$  : Minimum voltage of the pack, in Volts

## 4 Operating modes

### 4.1 Drive mode

The bus is in drive mode for the trips between the garage and the bus line but also in service during the trips between two charging stations. In this mode each energy source is supplying independently or in combination the consumers:

1. The consumers are supplied primarily by the EDLC pack. In order to maximize the efficiency, the braking recovery energy from the drive motor is also sent to the EDLC pack;
2. When the EDLC pack is almost empty ( $SOC < 20\%$ ) some energy is transferred from the battery pack to the EDLC pack. This mode compensates the power lack of the battery pack;
3. If EDLC pack is totally empty or out of service, the consumers are supplied only by the battery pack. A limitation is applied if the power requirement is too high.

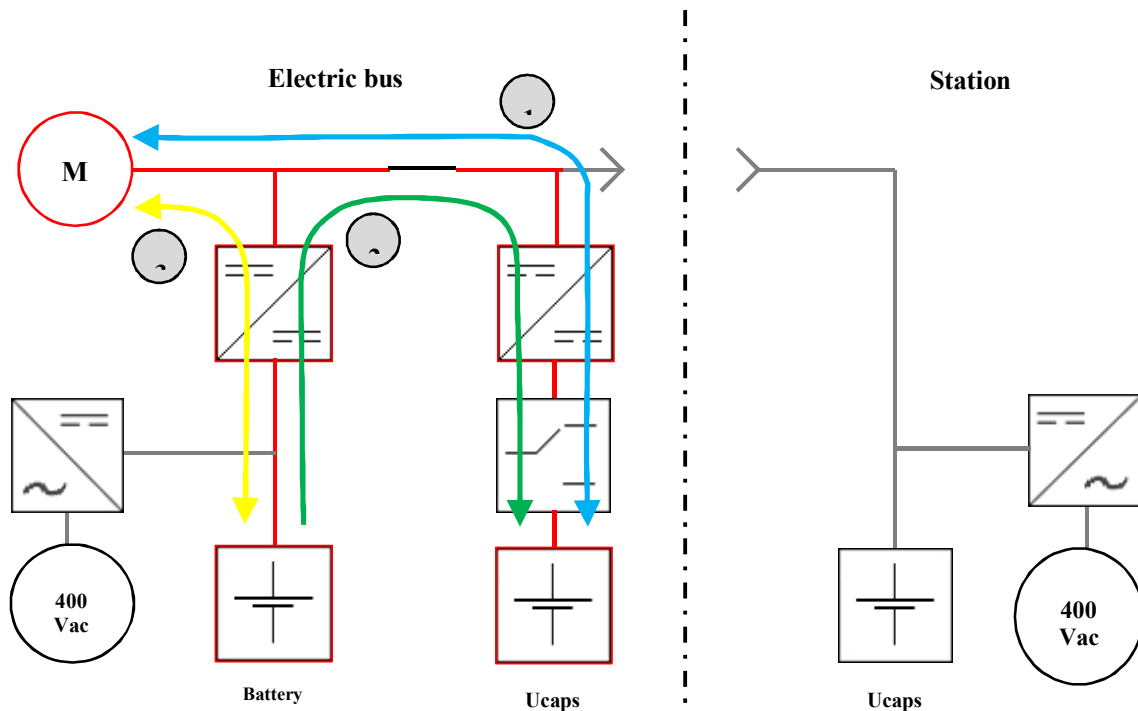


Figure 5: Power flows in drive mode

### 4.2 Charge mode

The bus is in charge mode when in front of a station with the parking brake activated. The sequence starts with the inhibition of the parking brake release. Then following sequence is engaged:

The EDLC pack is isolated from the rest of the system thanks to a contactor;

As a consequence the consumers are supplied by the battery pack in this mode

When the bus is connected to the station, a dc to dc converter controls the energy transfer from the EDLC pack of the station into the EDLC pack of the bus.

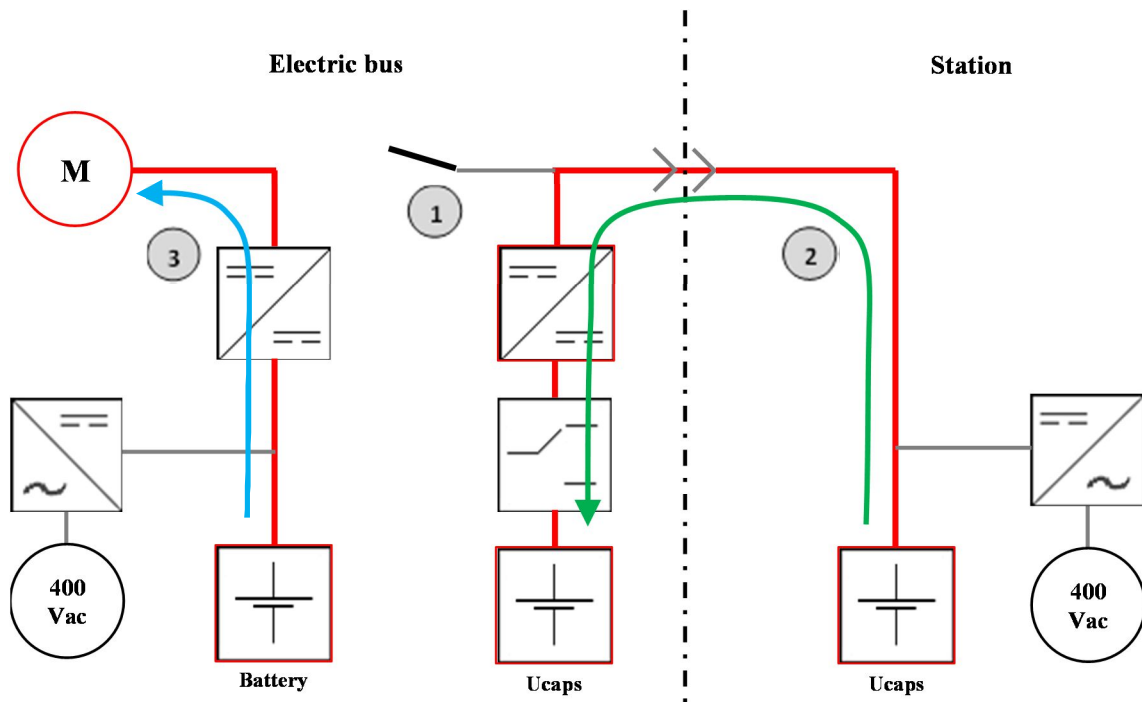


Figure 6: Power flows in charge mode

Another mode is applicable at terminal stations when the energy transfer between EDLC packs is over. In this case, the bus can stay connected during the residual waiting time and recharge its battery:

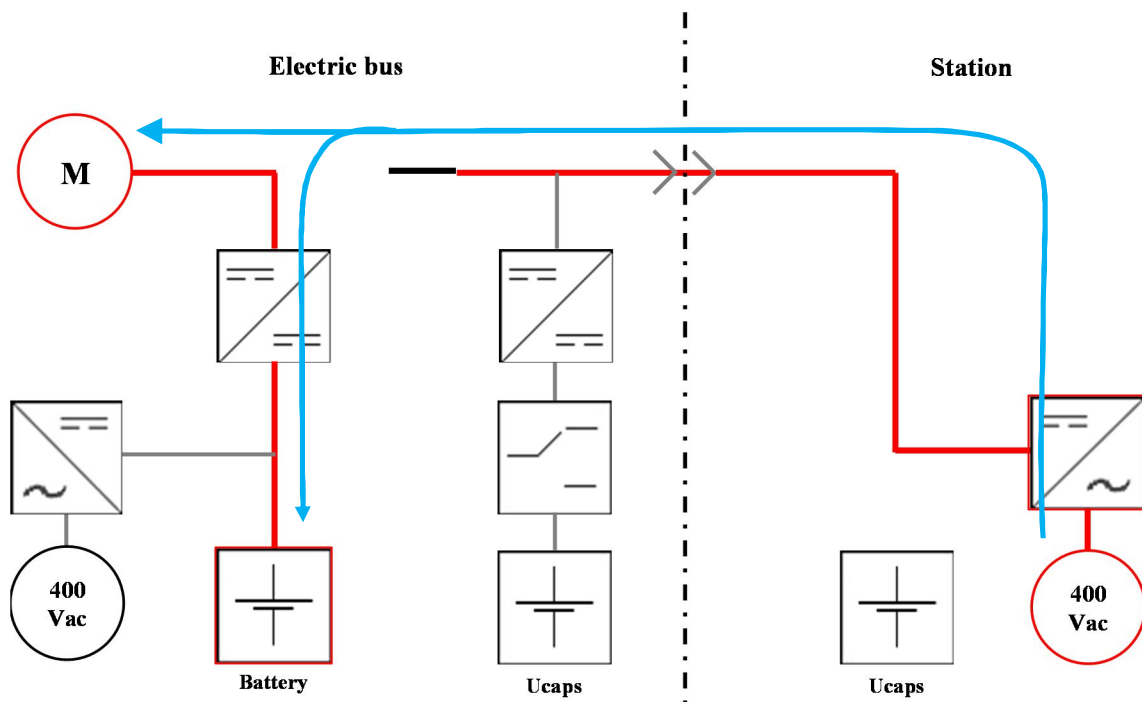


Figure 7: Recharge of the battery at terminal stations

### 4.3 Energy use between sources

The use of the energy between EDLC and battery is analyzed according to data collection from the demonstrator operation at the airport of Nice (South of France). The data described below are from the 22th of October 2015. Operation conditions: no air conditioning, 30 passengers on average;

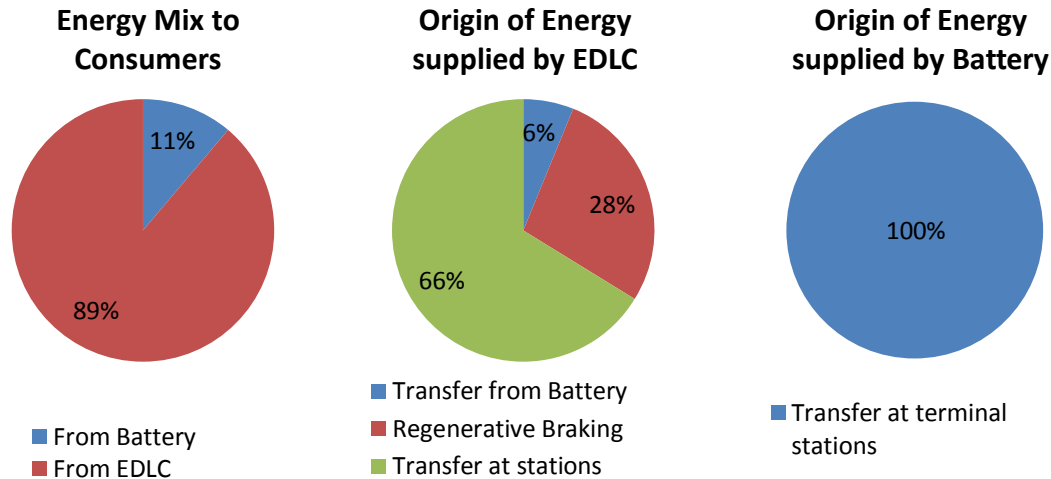


Figure 8: Energy mix

#### 4.3.1 Analysis

As expected, the energy supplied to the consumers is mainly coming from the EDLC pack;

The energy supplied by the EDLC pack is essentially coming from the energy transfers at the charging stations (66%). The energy recovered through the regenerative braking isn't worthless and represents 28% of the energy supplied by EDLC or around 25% of the global consumption;

The battery pack can stay at the same energy level thanks to the recharge phases at the terminal stations. Thus the possibility to skip a station and the back-up range in case of failure of the EDLC is guaranteed all along the service

## 5 A question of savings

### 5.1 Save planet

- No noise
- Zero emissions
  - Nor pollutants or particles: CO, NO<sub>x</sub>, SO<sub>x</sub>
  - Greenhouse gases emissions reduction : 259kg CO<sub>2</sub> eq / day (10) (11)

### 5.2 Save money

- 92 liters of fuel saved every day (12)
- 15€ only per day in France (13)
- Station's installation on the pavement to avoid heavy roadworks
- Simple concrete base of 1m<sup>3</sup>
- No energy storages replacement over bus life-time

## 6 And a question of results



**10 000 kilometers travelled and 3500 energy transfers** done since the completion of the test.

Operated in Nice Airport by transdev since February 2015, the first line includes one full electric standard bus of 12 meters and 6 charging stations.

The shuttle makes a tour between terminal 1, terminal 2 and car parks.

## 7 Next steps

1. 12 cities are currently interested by the system for their bus lines in France and our project team is working on dedicated offers based on their own operations.
2. Adapt our product to the North American market specificities.

## 8 A comparison with other charging technologies at the bus stops or on-road

Table 2: Comparison between different types of charging technologies (14) (15)

|                                  | Overnight charging e-bus                                                        |                                | Dynamic charging e-bus |                                | Opportunity charging e-bus     |             |                                                                  |               |
|----------------------------------|---------------------------------------------------------------------------------|--------------------------------|------------------------|--------------------------------|--------------------------------|-------------|------------------------------------------------------------------|---------------|
| Technology                       | Conductive                                                                      | Wireless                       | Conductive             | Wireless                       | Wireless                       |             | Conductive                                                       |               |
| Location                         | Depot                                                                           | Depot                          | Online                 | Online                         | At stops                       | End-Of Line | At stops                                                         | End of Line   |
| Charging time                    | 4-8h                                                                            |                                | N/A                    | N/A                            | < 30 sec                       | 5 to 15 min | < 30 sec                                                         | 3-15 min      |
| Charging Power                   | x to X kW                                                                       | 10                             | N/A                    | N/A                            | 60-200kW                       | 60-200kW    | 200 to 600 kW                                                    | 200 to 600 kW |
| Energy transfert Source          | Top, Ground, Lateral                                                            | Ground                         | Top, Ground            | Top, Ground                    | Ground                         |             | Top, Ground, Lateral                                             |               |
| Type of contact                  | Manual Socket, Pantograph, Inverted pantograph, ground base, Lateral connection | Inductive Power Transfer (IPT) | Overhead catenary      | Inductive Power Transfer (IPT) | Inductive Power Transfer (IPT) |             | Pantograph, Inverted pantograph, Ground base, Lateral connection |               |
| Vehicle Price                    |                                                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Infrastructure                   |                                                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Online (costs)                   |                                                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Depot adaptation                 |                                                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Power Supply                     |                                                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Distribution / connection        |                                                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Autonomy                         |                                                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Operation                        |                                                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Energy Transfert                 |                                                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Efficiency                       |                                                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Transportation                   |                                                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Capacity                         | When considering HVAC equipment                                                 |                                |                        |                                |                                |             |                                                                  |               |
| Battery Lifetime / Battery Costs |                                                                                 |                                | Unknown or N/A         |                                |                                |             | For Supercaps based solutions                                    |               |

## 9 Referencing

### 9.1 Sources

- (1) Data according to IRIZAR i2e and VDL Citea Electric datasheet
- (2) Data for quick-charge at each station according to data from PVI
- (3) Data for fast-charge at end of line according to Bombardier Primove and Volvo Bus datasheet
- (4) Battery bus: Battery with high energy density (LiFePo4 , NMC, or Sodium Nickel), lifetime of 2 000 to 3 000 cycles, generally no cooling system for lifetime enhancement. Quick-charge at each station : Lifetime according to estimations made by different EDLC manufacturers. Fast-charge at end of line : Power battery (LTO mainly), cooling system for lifetime optimization, lifetime of 10 000 cycles
- (5) The use of a battery bus is the same as a standard diesel bus. The quick-charge at each station offers a good flexibility as no charging time at the end of line is required. For fast-charge at the end of line, the required time to charge the battery can be seen as a constraint.
- (6) The use of a battery bus is the same as a standard diesel bus. For quick-charge at each station, the modification of the bus line will require to move some stations. For fast-charge at the end of line, the bus line can be changed but not the terminal stations.
- (7) For the battery bus, the initial investment is low because no infrastructure is required. For opportunity charging at each station, one station is required every 500 meters. This means a high investment in infrastructure, but no replacement is needed for the supercapacitors. Investment is medium for opportunity charging at the end of line because of the fast-charge stations at each end of line
- (8) The TCO calculation includes the initial investment for infrastructure and buses and the cost for battery replacement (only for battery bus and fast-charge at the end of line). The cost of electricity and for maintenance is considered the same for all solutions
- (9) According to numerical simulations on typical duty cycle from Maxwell Technologies, <http://www.maxwell.com>, and IOXUS, <http://www.ioxus.com>.
- (10) CO<sub>2</sub> equivalent emissions per km for a diesel bus km – CO<sub>2</sub> eq emissions per km for our full electric bus (based on the electric consumption) x numbers of kilometers per day (based on 200km per day)
- (11) CO<sub>2</sub> equivalent emissions figures are provided by the French environmental agency [on GHG databasis](#)
- (12) Based on the average consumption of a standard diesel city bus per kilometer considering an average tour of 200km per day: <http://www.scania.com/products-services/trucks/environment/epd/calculator.aspx>
- (13) Based on the average cost of electricity per kWh in France (1,03kWh x 100km x 0,1535€), [Pegase databasis](#)
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## Authors



### **Walter Delage**

After being graduated in Marketing & Communication, he successfully bet on Sustainable Development in 2008 by joining the MBA of sustainable performance from ISC Paris School of management (France). For 6 years, he played role in the field of energy within the dutch company SHV, global leader in the distribution of Liquefied Petroleum Gas, where he was responsible for communication and sustainable development. He joins PVI to meet the challenge of the electric innovation as marketing manager.



### **Mathieu Grenier**

He is graduated from the engineering school “Arts et Métiers Paris Tech” (France) and from the University of Karlsruhe (Germany) since 2009. Highly oriented towards innovation and project development he began his career at PVI in 2009 as a project leader on the WATT program. This program will be successfully ended in 2016 after a test field of 18 month. In between (2010-2013) he also had the opportunity to challenge its leadership through the development of full electric buses and trucks. Since 2015, he's in charge of the development of the WATT program and specially the evolution of the system towards high-capacity buses and bus rapid transit lines.