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From Battery Manufacturing to Smart Grids: Towards a Metaverse for the Energy Sciences**

Alejandro A. Franco,*[a, b, c, d] Emilie Loup-Escande,[e] Goran Loiseaux,[e] Jean-Noël Chotard,[a, b] Diana Zapata-Dominguez,[a, b] Jan Ciger,[f] Aubin Leclere,[f] Lucie Denisart,[a, b] and Romain Lelong[f]

We present two digital-based educative games aiming to engage students and the general public with battery sciences. The first one is a multiscale simulator in Mixed Reality of a battery-powered Electric Vehicle (EV) interacting with an Electrical Grid. One of the players drives the EV in a Virtual Reality (VR) environment where the EV can be recharged, and the other players control the electricity produced, distributed, consumed and stored by interacting with 3D-printed devices. The second educative game is a digital twin of a lithium ion battery manufacturing pilot line, which can be played from an Internet Browser or by using VR hardware. The key steps of the manufacturing process of cylindrical cells are represented in an interactive way. In this concept, we reviewed the working principles of our games, their implications for motivation, engagement and learning, and why they pave the way towards new ways of collaborative R&D in the battery field.

1. Towards a Metaverse for Energy Storage Education

Covid-19 pandemics times forced our societies to suddenly change our habits. Besides the encouragement of social distancing and home working, it triggered travel restrictions and specific rules for population circulation.[1] This change in habits could be seen as a mirror of what our societies would experience on Earth if the undergoing Climate Change triggers unprecedented damage levels.[2] However Covid-19 pandemics restrictions have also significantly accelerated the expansion of digitalization in our ways of working and educating, with a multiplication in the usage of software for remote meetings and for collaborative work in the cloud.[3] Social distancing and remote working also made the concept of metaverse to gain significant attraction.[4] A metaverse is defined as an environment where multiple types of technologies enable multisensory interactions with virtual environments, in which digital objects and real people coexist. Such technologies include Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality, and the resulting metaverse gives the promise to become the next evolution of social connection.[5,6]

Furthermore, VR and AR are emerging as powerful tools for educational purposes.[7–10] While VR refers to putting the trainee in full immersion in a digitally-created environment by making him/her to wear VR glasses (Figure 1a), AR, through holographic glasses or tablets, overlays digital information in the real world.[11,12] Mixed Reality is another emerging technology that usually refers to an AR experience where the user can interact with the projected holograms by receiving feedback from them (Figure 1b).[13] In a couple of previous publications we have introduced for the first time a series of VR serious (or educative) games we have developed for education and popularization of electrochemical energy storage (batteries)

[a] Prof. Dr. A. A. Franco, Dr. J.-N. Chotard, Dr. D. Zapata-Dominguez, L. Denisart
Laboratoire de Réactivité et Chimie des Solides (LRCS), UMR CNRS 7314
Université de Picardie Jules Verne, Hub de l'Energie
15, rue Baudelocque, 80039 Amiens Cedex, France
E-mail: alejandro.franco@u-picardie.fr
[b] Prof. Dr. A. A. Franco, Dr. J.-N. Chotard, Dr. D. Zapata-Dominguez, L. Denisart
Réseau sur le Stockage Electrochimique de l'Energie (RS2E)
FR CNRS 3459
Hub de l'Energie
15, rue Baudelocque, 80039 Amiens Cedex, France
[c] Prof. Dr. A. A. Franco
ALISTORE-European Research Institute, FR CNRS 3104
Hub de l'Energie
15, rue Baudelocque, 80039 Amiens Cedex, France
[d] Prof. Dr. A. A. Franco
Institut Universitaire de France
103 Boulevard Saint Michel, 75005 Paris, France
[e] Dr. E. Loup-Escande, G. Loiseaux
Centre de Recherche en Psychologie: Cognition, Psychisme et Organisations (CRP-CPO), UR UPJV 7273
Université de Picardie Jules Verne
1, Chemin du Thil, 80025 Amiens Cedex 1
[f] J. Ciger, A. Leclere, R. Lelong
Reviatech SAS
Parc Technologique des Rives de l'Oise, Rue les Rives de l'Oise, 60280 Venette, France

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Figure 1. a) Two of our students playing our VR educative games, by using HTC Vive hardware; b) a person using Microsoft® Hololens Mixed Reality glasses.

science[14,15] and for which we won one of the French Prizes for Pedagogical Innovation in 2019.[16] These VR games include one allowing to build crystallographic structures by applying symmetry operations just with the hands, another game allowing to calculate the geometrical tortuosity of electrodes by flying through them, another one allowing to explore materials in 3D and other two games allowing to drive and Electric Vehicle (EV) powered by three types of battery technologies (Lithium Ion, Lithium Sulfur and Lithium Air) in a virtual environment. In one of these publications, we have also presented the prototype of a new type of educative game, called *Smart Grid MR* implicating a player driving a battery-powered EV in the VR environment in interaction with players acting on 3D-printed power generators (one wind generator, one solar panel and one water funnel).[14] MR in the name of this educative game stands for Mixed Reality but in the sense of putting the virtual environment in interaction with objects of the real world. Indeed, in this educative game, blowing a wind generator and illuminating a solar panel generates virtual power which is stored in a Redox Flow Battery (RFB) in the virtual environment giving immediately power to stations where the EV can be recharged. Flowing water through a funnel triggers rain in the VR environment, increasing the water level in a virtual dam and generating extra power sent to the virtual RFB. In this educative game, the goal of the EV driver is to collect as much as gifts as possible (randomly located on the virtual roads) by escaping from pirate trucks and by avoiding the battery in the EV to become fully discharged. In this educative game, the VR headset (HTC Vive) is connected via a cable to a computer simulating the virtual environment, while the actionable 3D printed objects are connected to the computer via Bluetooth. Overall, this educative game allows involving four simultaneous players: the EV driver evolving in the VR environment and the three persons acting on the 3D-printed power generators.

We have shown that these VR/MR educative games ease the understanding of the complex concepts behind the micro-structure of the materials and their operation principles in rechargeable batteries. They also increase significantly the engagement and motivation of the students.[14,15] Because of this, we have used them in numerous science festivals as they constitute very efficient tools to popularize complex battery science.

First, in the present Concept we report a major upgrade of the Smart Grid MR educative game, called here by us *Smart Grid MR 2.0*, with new and more realistic functionalities allowing to involve up to 16 players simultaneously. We first describe the technical characteristics and functionalities of this new educative game. Then we present a detailed study about the impact of the game on the motivation, learning and collaborative skills of Master students, a type of study that to the best of our knowledge, has never been reported before for a MR platform hybridizing VR with real objects. We also introduce a new VR educative game also playable from an Internet browser for maximal outreach, SIMUBAT 4.0. This is a digital twin of the manufacturing pilot line of lithium-ion batteries (LIBs) in our laboratory. It allows exploring in an interactive and immersive way the manufacturing process of LIB cells, by placing the player in a digital twin of a battery pilot line. Furthermore, we discuss why these educative games pave the way towards a new way of experimenting with the energy storage sciences and how they can support collaborative R&D activities in the metaverse. We finally conclude and indicate future directions for our work.

2. Smart Grid MR 2.0: The Working Principles

Renewable energies constitute one of the keys for the transition to a more sustainable World, while energy storage technologies such as RFBs can be used to regulate the timing between electricity production from renewable energies and consumption, especially when they are part of smart grids, i.e., electrical grids which have the capability to manage in real time and in the most efficient way the energy flow depending on the electricity production and consumption.[17]

Our new educative game Smart Grid MR 2.0 presented in this Concept, aims to represent the electrical grids working principles, where the smartness, i.e., the management between power production, consumption, distribution and energy storage, is managed by the players (Figure 2).

Smart Grid MR 2.0 can be seen as a multiscale simulator, because it embeds mathematical models representing different aspects:

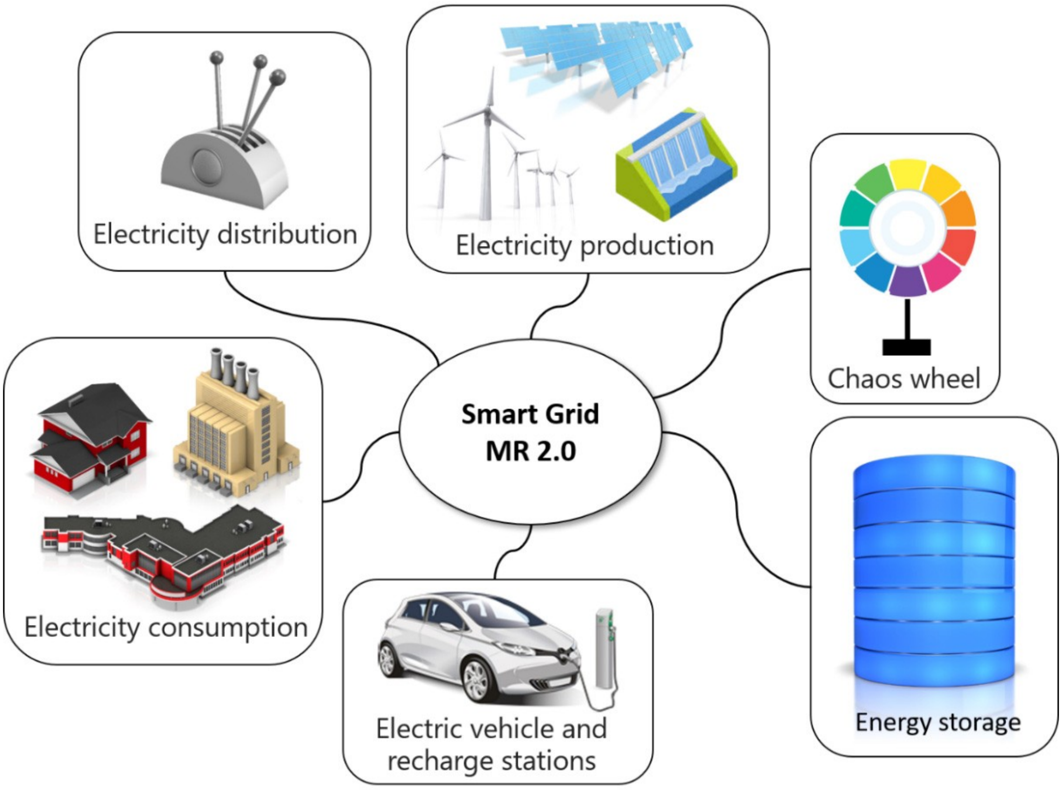

Figure 2. Concept behind our educative game Smart Grid MR 2.0.

- The electrical grid encompassing electrical energy generation, distribution, storage and consumption;
- An EV empowered by a rechargeable battery;
- The electrode materials inside the rechargeable battery cells;
- The RFB storing energy from the electricity available in the grid.

Smart Grid MR 2.0 involves 1 player evolving in the VR environment and up to 15 players evolving in the real world. The actions undertaken by the players in the real world affect the VR environment and the player progressing in it. The latter mission is driving the EV by escaping from pirate trucks, by avoiding colliding with randomly appearing barriers across the virtual roads and by avoiding the EV battery to fully discharge. The EV driver must collect as many gifts as possible while circulating on the roads of a virtual city and its peripheric areas. Those gifts appear randomly on the roads, one after the other, and their collection gives points to the EV driver. In contrast to our past EV educative games in VR and similarly to our past Smart Grid MR educative game,[15] there is not limit in the number of gifts that can be collected in Smart Grid MR 2.0. After a configurable number of points the game level is automatically upgraded, which implies that more pirate trucks will appear and that the barriers randomly blocking the roads will appear more frequently. The EV can be recharged by the VR player by parking it for a few seconds in one of the 4 recharge stations available in the virtual city. These recharge stations are powered with the energy stored by the RFB. The energy stored (ES) by the RFB is given by

$$ES = \sum_i G_i - \sum_j C_j \tag{1}$$

where G_i stands for the energy generated by the generation entities (e.g., solar panel) and C_j the energy consumed by the consumption entities (e.g., house). The additions in Equation 1 can imply all, some or any production or consumption entity, depending on how well the RFB is interconnected with the rest of the electric grid at a given time.

At the beginning of the educative game the VR player has to choose the type of battery and electrode properties he/she is going to use in the EV. As in our previous educative game Smart Grid MR, the driver can power his/her EV with one of three battery technologies: LIB, Lithium Sulfur Battery (LSB) or Lithium Oxygen Battery (LOB) (Figure 3).

For the LIB case, the driver can choose the type of active material for the negative electrode (graphite, Lithium-titanate oxide –LTO–), and the positive electrode is based on Lithium Manganese Cobalt Oxide –NMC– (but other chemistries can be added). For the LSB case, the virtual battery cell is constituted of a negative electrode made of Lithium and a positive electrode made of a carbon/sulfur composite.[14,18,19] Here the driver can choose the sulfur loading. For the LOB case, the virtual battery cell is constituted of a negative electrode made of Lithium and a carbon-based positive electrode.[14,20,21] In this case, the driver can choose the positive electrode porosity and oxygen pressure. The autonomy of the EV battery is made dependent on the materials and electrode properties through

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Figure 3. One of the electric cars that can be chosen by the VR driver at the beginning of our Smart Grid MR 2.0 game. We can also see the menu in which the type of battery and the types of electrode materials can be chosen.

	House	Industry	Offices	Wind	Solar	Hydro
A	●	●●	-	-	-	●●●
B	●	●	-	●●●	●●●	-
C	●●●	-	●●●	●	●	-
D	●●●	●	-	●●●	●	●

Figure 5. Relative weight of different types of electricity consumption and production entities in the four zones of the virtual city.

mathematical formulas implemented in a Python script.[14] These formulas are editable, and therefore the game can be extended to any kind of material and battery technology. Other aspects such as active material loading in the case of LIBs or electrolyte volume in the case of LSBs can also be easily included.

Once the driver has chosen his/her battery technology and associated properties, he/she starts driving the EV along the roads of the virtual city and its peripheric areas (Figure 4). The latter is constituted of four interconnected zones (A, B, C and D) containing different amounts of residential, commercial, industrial and power generation entities. Figure 5 summarizes the relative amounts of houses, commercial buildings, factories and power generators based on the wind (windmills), solar energy (solar tower and panels) and hydraulic energy (water dam). A tidal wave power generator (fully controlled by the game following a realistic tide cycle) is available in zone D.

The houses, commercial buildings and factories consume electricity, and their consumption rates are controlled through three real 3D-printed devices representing a house, an office building and a factory, respectively (Figure 6). The electricity consumption rates in these devices are controlled via regulators (indicated with arrows in Figure 6) by three players acting in the real world. The rate/regulator spin ratio can be configurated through a Python script available in the computer executing the game and simulating the virtual environment. These devices are connected via Bluetooth to this computer. The action on houses, offices and factories is not distinguished between zones, and therefore the players need to get familiarized with Figure 5 before acting on these objects: they will trigger electricity consumption at different rates between zones depending on their chosen intensity and the relative number of houses, buildings and factories available in each of the zones. This determines the overall electricity consumption rate for each of the zones. The players acting on these objects collect more points if they consume more electricity. This is counted automatically by the game software.

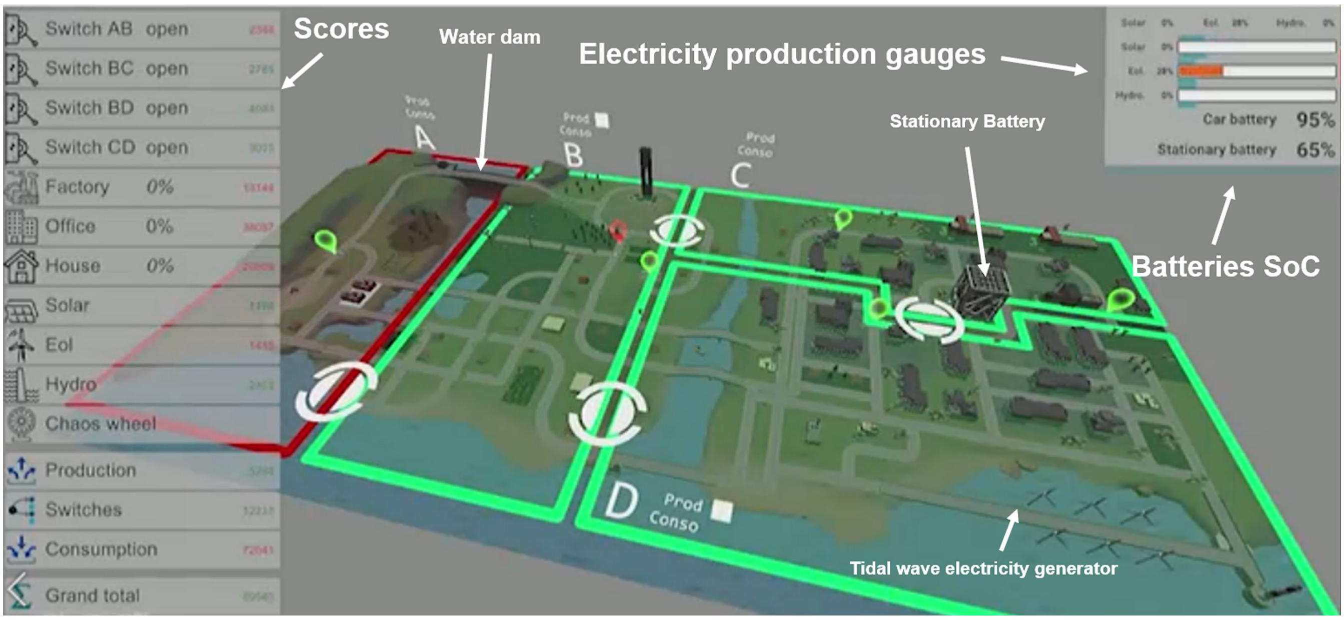

Figure 4. A snapshot of the virtual map of Smart Grid MR 2.0 in which the EV driven by the VR player evolves. The map is divided in four zones that dynamically turn their colour from green to red if there is lack of electricity in the corresponding zone.

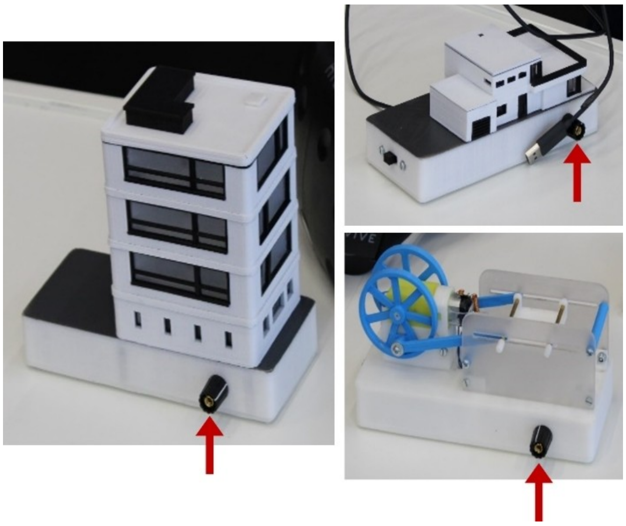

Figure 6. The interactive 3D-printed representations of the electricity consumption entities in our Smart Grid MR 2.0 educative game. The red arrows indicate the wheels allowing to the players to regulate the electricity consumption intensity.

Five players can interact with five real 3D-printed wind generators, while one player can interact with a real 3D-printed solar panel and another player can interact with a real 3D-printed water funnel (Figure 7). All these power production devices are connected via Bluetooth to the computer simulating the real environment. The power production rate in each zone depends on the type of generator used, the way it is used (e.g., the intensity of the light used to illuminate the solar panel, the intensity of the wind-blown on a wind generator) and their relative number in each of the zones. When an action is performed on them, these devices trigger electricity generation in the virtual environment. The electricity production rates are configurable via a Python script that can also consider the pales inertia or other realistic engineering aspects of the wind generators. A weather simulator (accounting for realistic cycles between rain, sun and wind) provides dynamic indications via a dashboard on which type of electricity generator to use at each instant of the game (detail in Figure 7b and indicated as "electricity production gauges" in Figure 4). The players acting on the generators should follow these indications as much as possible to collect as much as points as possible. Such points are automatically counted by the game as a function of the agreement between the types of electricity generators used and the ones requested by the weather dashboard.

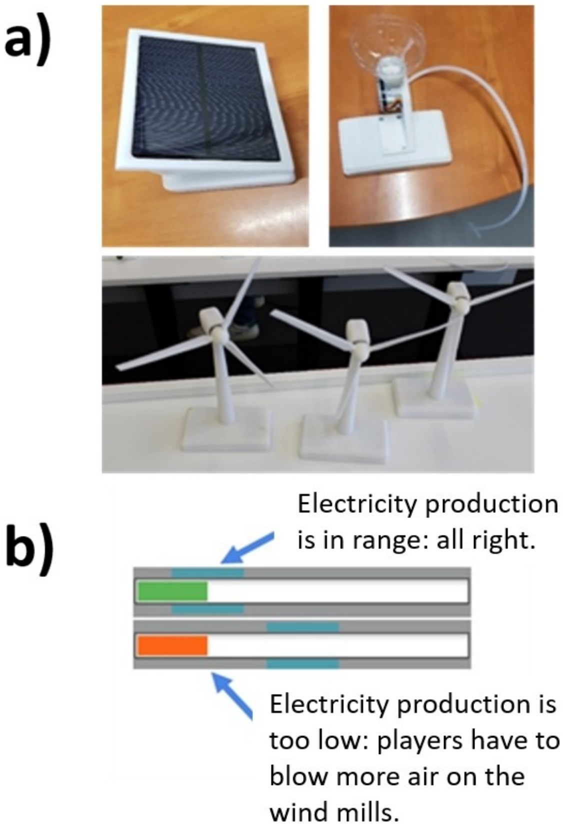

Figure 7. The 3D-printed devices allowing to control the electrical energy generation in the educative game Smart Grid MR 2.0, and the weather simulator-driven dynamic dashboard.

Four players interact with four real switches, which can adopt "open" or "close" states (Figure 8). These switches act at the border between zones A and B, B and C, C and D, and D and A. By putting a switch between two zones in the "open" state, electricity flows from the zone with an excess amount to the one having less. This can be used to compensate for the lack of electricity in a given zone. Proper electricity distribution between zones (i.e., ensuring that none of the zones is lacking of power) allows the "switch" players to collect points, automatically calculated by the game. The switches act via Bluetooth on the virtual environment simulated by the computer.

Finally, a player interacts with a real "Chaos" wheel also connected via Bluetooth with the computer in which the virtual environment is simulated (Figure 9). By spinning this wheel, it will randomly stop on one of the several indicators inducing virtual catastrophes: this includes the instantaneous full discharge of the stationary battery, the switches which become frozen for 10 seconds (mimicking issues in the power distribution network), the wind mills, the solar panel or the water dam which cannot produce power for 10 seconds. The wheel can also stop in a spot where any catastrophe is produced. The emergence of these catastrophes pushes the players to redesign on the fly the strategies to maintain the proper balance between electricity production, consumption, distribution and storage.

A grand total of collected points is calculated on the fly by the game from the number of points collected by each individual player acting on the different 3D-printed objects (*cf.* Figure 4).

Smart Grid MR 2.0 can be used under two possible scenarios: competitive one between individual actors or group of individuals having a specific type of action (electricity generation, distribution, consumption, distribution), or collaborative one aiming at ensuring the power sustainability of the electric grid. In this version of the game, the points cumulated

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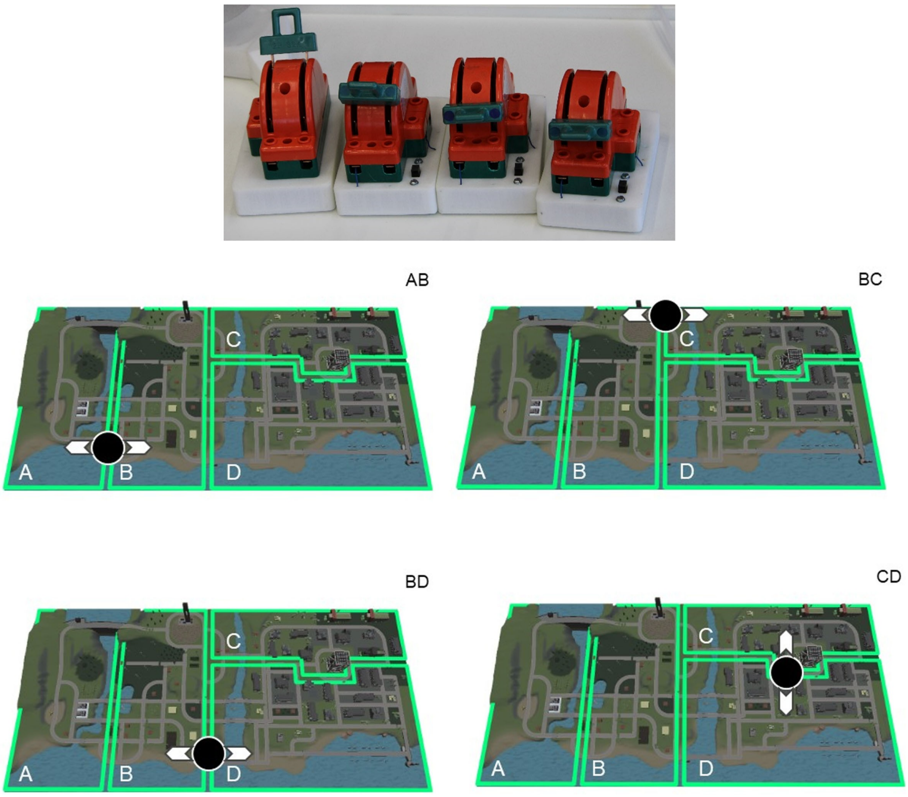

Figure 8. The switches allowing to control the flow of electricity between zones in the virtual environment of our educative game Smart Grid MR 2.0.

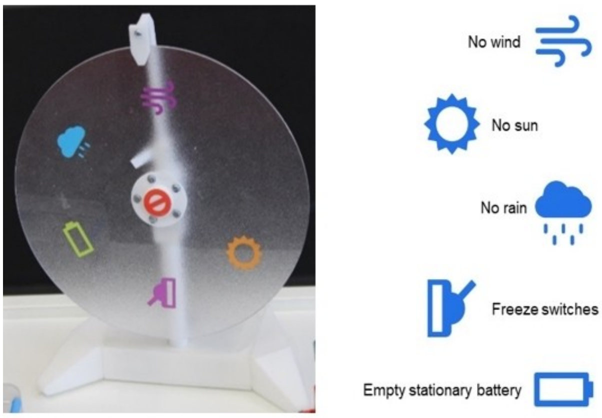

Figure 9. The "chaos" wheel in our educative game Smart Grid MR 2.0, which is used by one of the players to randomly and temporarily produce breakdowns and other problems in the virtual environment that the other players have to manage.

by the EV driver through the gifts he/she collects do not contribute to the grand total of points. Nevertheless, if the EV driver losses his/her mission (either because he/she is captured by one of the pirate trucks, he/she collides a barrier or the EV battery becomes fully discharged) all the players loss the game.

The game does not have predefined duration. It can last several hours, depending on the players performance, but in practice, our students have played for durations of *ca.* 2 hours. Smart Grid MR 2.0 allows saving an ongoing game session for a later time, and therefore players can organize their strategies and manage fatigue as they wish.

Illustrations of the Smart Grid MR 2.0 in action are provided in Figures 10, 11 and 12, and a video showing the students playing the game is provided as Supporting Information file.

3. Smart Grid MR 2.0: Pedagogic Impact

Since its creation by us in 2020, Smart Grid MR 2.0 was regularly used in practical lectures addressing the topic of energy conversion and storage, in particular with our Master level students at the Université de Picardie Jules Verne (Amiens, France), and also in science festivals and specific demonstrations to visitors of our university. In the following we report a detailed study we have performed in order to characterize the pedagogic impact of this educative game. We investigated the game learning outcomes,[15] motivation by the students,[22,23] cybersickness[24], immersion and presence,[25] student experience,[26] and collaboration between them. After a professor (Prof. Alejandro A. Franco) delivered a series of 8 lectures of 1 hour 30 minutes duration on technologies for energy conversion and storage, a volunteer group of 8 students (2 women and 6 men, aged between 22 and 27 years old – mean = 24.4, standard deviation = 1.92–) of our Erasmus+ Master Program "MESC+" (Materials for Energy Storage and Conversion)[27] were requested to score the maximum number of points by both managing the MR electrical grid infrastructure and by

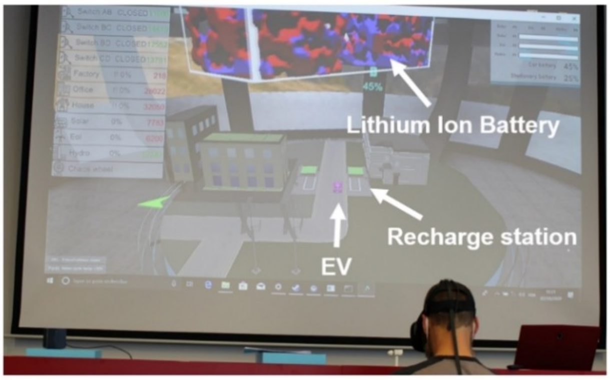

Figure 10. A snapshot of what is seen by the EV driver evolving in the VR environment.

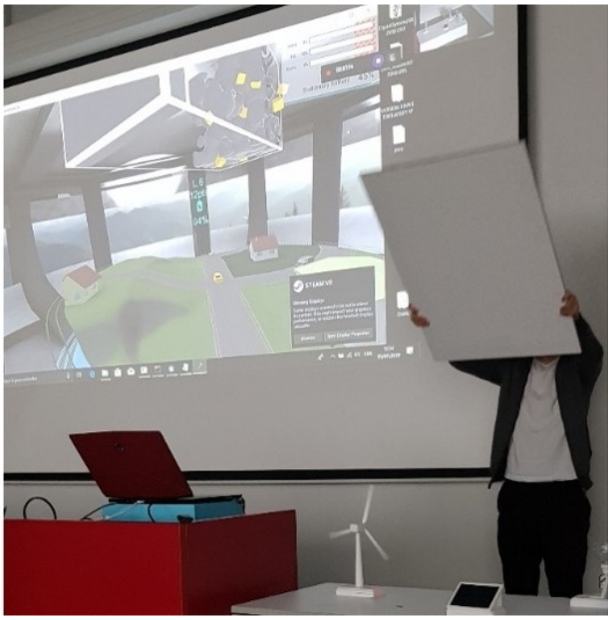

Figure 11. A student producing air flow towards one of the 3D-printed wind-driven electric generators. The red laptop is the hardware in which the VR environment is simulated. All the 3D-printed devices communicate with it via Bluetooth.

collecting as much as gifts as possible in the VR environment (cf. Figure 12). The students were requested to complete a series of questionnaires before and after playing the game.

The first questionnaire filled in before the game task contained 19 questions: 3 demographic items (age, gender, nationality), 9 items about familiarity with technologies including the ones supported on virtual, mixed or augmented reality, adapted from the Likert scales-based questionnaire devised by Loup-Escande *et al.*[15] (e.g., “If you play video games, how often do you play using a controller?”, “If I hear talking about a new technology I try to test it as fast as I can”), and 7 items on familiarity with the energy topic (e.g., “Concerning electricity production, what types of renewable energies are commonly used?”).

Several subjective questionnaires were completed by the students before and after the game task and these were, first, the Situational Motivational Scale (SIMS), second, the Simulator Sickness Questionnaire (SSQ), and third, a knowledge questionnaire. The SIMS questionnaire is typically used to measure motivation.[28] It contained 16 items rated on 7-point Likert-like scales scored from 1 to 7: 4 intrinsic motivation items, 4 identified regulation items, 4 external regulation items and 4 amotivation items. The SSQ questionnaire was used to measure cybersickness and contains 16 items rated on 4-point Likert-like scales scored from 0 to 3: 9 nausea items and 7 oculomotor discomfort items.[29] The knowledge questionnaire consisting in 7 items was used to assess the students' understanding after completing the game task. The 7 items were questions on the knowledge acquired about the energy topic (e.g., “What types of renewable energies are commonly used to produce electricity?”). For this questionnaire, we assigned a possible total score of 12 points to each participant (for each question, 1 point per correct answer, 0 point for a wrong answer).

The subjective questionnaires completed only after playing our educative game were, first, the AttrakDiff, second, the Immersion Tendencies Questionnaire, and third, the Presence Questionnaire. The AttrakDiff questionnaire is typically used to measure the user-experience: it contained 28 items rated on 7-point Likert-like scales scored from -3 to $+3$ as suggested by Hassenzahl:[30] 7 pragmatic quality items, 14 hedonic quality items and 7 appealingness quality items. Immersion was measured using 18 items from the Immersion Tendencies Questionnaire and presence was measured using 19 items from the Presence Questionnaire inspired from Witmer and Singer (1998).[31]

Once the participants have answered the pre-game questionnaires, a professor (Prof. Alejandro A. Franco) explained the aims and presented the peripherals to be used and the actions to be undertaken in order to accomplish our educative game goal. Then, the participants played the game. Finally, the students completed the post-game questionnaires.

For the numerical results extracted from the questionnaires, we ran a test of normality (Shapiro-Wilk test[34]). The data were analyzed using the nonparametric Wilcoxon test[35] when the Shapiro-Wilk test indicated a non-normal sample distribution (p-value <0.05), while a paired *t*-test[35] was performed when the Shapiro-Wilk test indicated that the sample distribution is not significantly different from a normal distribution (p-value >0.05).

We have recorded 4 videos capturing the students' interactions with each other and with our educative game during its use. The video recordings lasted in average 7 minutes 50 seconds (minimum = 3 minutes 30 seconds; maximum = 12 minutes 34 seconds). We have also recorded the verbalizations related to the actions and mental operations implemented in these situations, the actions of the students, and the dialogues involving the students and the professor. These were verbalizations simultaneous to the completion of the game task,[32] but also dialogues between participants about the game or their ongoing activity. The audio-recordings were

Figure 12. Smart Grid MR 2.0 being played by a group of MESC+ Master students at the Université de Picardie Jules Verne (Amiens, France).

made using a dictaphone and the CamStudio software[33] was used for the audio files post-processing. The audio recordings were transcribed verbatim and constituted our corpus composed of 111 lines. We have then proceeded with the segmentation of the corpus into units (one unit corresponding to each participant's speech), the characterization of the participant who produced the unit (role of the speaker in the game, e.g., student in charge of the solar panel), the coding of each unit in order to characterize its type of contribution in the activity, and the grouping of the units into an activity chronicle.

Following the coding scheme of Darses et al., developed for the analysis and modeling of cognitive activities of collective design,[36] the content of each unit was coded according to its type (query or assertion), the associated cognitive activity (generation, evaluation, information) and the subject concerned (data, solution, object, goal, procedure, task). Table 1 defines each of these categories. Then, and as recommended by Corroyer and Wolff[37] to estimate the magnitude of the association between two categorical variables, we used Cramer's V2[38] and Relative Deviation (RD), as in other studies.[39] Cramer's V2 lies between 0 and 1. The association is conventionally considered as strong when Cramer's V2 > 0.16, as weak when Cramer's V2 < 0.04, and as intermediate between the two scores.[37] The RD is calculated on the basis of a comparison between observed and expected frequencies (i.e., those that would have been obtained if there was no association between the two variables). There is attraction when RD is positive, and repulsion when it is negative. By convention, we retain only RD with absolute terms > 0.25.

In terms of results, first, the group of students was found to be technophile and familiar with VR-like technologies (mean = 29.88, standard deviation = 9.03, minimum = 20, maximum = 45). Given that the maximum total score that participants could obtain in the first questionnaire was 54 points and the minimum total score was 0 points, the theoretical average is consequently 27 points. Thus, since our sample obtained above 27 in average, we concluded that our participants are technophiles.

The learning outcomes were not better after using Smart Grid MR 2.0. Indeed, a Wilcoxon test revealed no significant difference in knowledge as no significant difference existed between the questionnaire score before using our educative game (mean = 9.75, standard deviation = 1.58) and the score after using it (mean = 9.50, standard deviation = 1.41).

Concerning the motivation perceived by the students, a paired-samples *t*-test showed non-significant difference for intrinsic motivation as no significant score existed between the questionnaire score before using our game (mean = 23.75, standard deviation = 2.25) and the score after using it (mean = 23.1, standard deviation = 3.27). The paired-samples *t*-test also showed a non-significant difference for identified regulation as a non-significant difference existed between the questionnaire

Table 1. Definitions and examples of speech types, associated cognitive activities and the subjects concerned.

	Category	Definition	Example
Type of content	Query	Question	*What is your score now?*
	Assertion	Affirmation	*There is a car*
Cognitive activity	Generation	Bring a new element according to the situation	*There is a gift to collect in the left direction*
	Evaluation	Action of judging an element according to the subject perception	*Yeah, he is really good*
	Information	Give explanation/knowledge on a specified element	*Three pirate trucks are really close, be careful!*
Subject	Data	A piece of information which is associated to the situation	*I am at level 6*
	Solution	A proposal made to solve a problem occurring during the utilization of the device	*Put oxygen pressure to 100% to increase the autonomy of the lithium-oxygen battery powering the car*
	Object	An object coming from the game	*Be careful, there is a barrier*
	Goal	Goal made by the students or the professor	*Come on guys! Let's get 30000 (points)*
	Procedure	A declaration made on the way used to reach the goal	*Turn in circle*
	Task	An action made to reach the goal	*Active transfer of electricity from zone B to zone A*

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score before using our game (mean = 18.38, standard deviation = 4.44) and the score after using it (mean = 20, standard deviation = 4). Moreover, a Wilcoxon test revealed no significant difference in extrinsic regulation as there was no significant difference between the questionnaire score before using our educative game (mean = 16, standard deviation = 6.70) and the score after using it (mean = 16.62, standard deviation = 5.95). However, a paired-samples t-test showed a significant difference for amotivation as a significant existed between the questionnaire score before using our educative game (mean = 8, standard deviation = 3.16) and the score after using it (mean = 10.63, standard deviation = 4.93, $t(7) = -2.42$, $p = 0.046$, two-tailed).

Furthermore, Smart Grid MR 2.0 does not cause cybersickness. Indeed, a paired-samples test showed a non-significant difference for cybersickness as a non-significant difference existed between the questionnaire score before using our educative game (mean = 7.86, standard deviation = 5.15) and the score after using it (mean = 6.14, standard deviation = 4.60).

Smart Grid MR 2.0 seems to bring immersion and a sense of presence. More precisely, immersion results show that focus (mean = 18/35, standard deviation = 2.94), implication (mean = 17.5/35, standard deviation = 5.45), emotion (mean = 11.75/28, standard deviation = 6.5) and gamification (mean = 10.75/21, standard deviation = 2.36) are high. Moreover, sense of presence results show that realism (mean = 24.25/49, standard deviation = 6.08), actionability (mean = 18.5/28, standard deviation = 6.86), interface quality (mean = 11.75/21, standard deviation = 3.10), examinability (mean = 15/21, standard deviation = 1.83) and self-assessment (mean = 10.25/14, standard deviation = 2.99) are also high.

Additionally, user experiences results show that ergonomic quality (mean = 35.71/56, standard deviation = 6.45), hedonic quality (mean = 33.29/49, standard deviation = 2.75) and appealingness (mean = 35.71/56, standard deviation = 3.95) are high.

Moreover, the pedagogical activity mediatized by Smart Grid MR 2.0 is characterized by an actual collaboration between students.

Table 2 shows the frequencies of the various collaborative cognitive activities according to the role of the students in the game and the professor. The collaborative cognitive activities observed were mainly "information" (73 %, e.g., "We need to recharge the stationary battery!"), and to a less extent, "generations" (14 %, *e.g.*, "Yes, maybe we can decrease the difficulty") and "evaluation" (12 %, e.g., "Can you try to drive the EV more slowly?"). Moreover, the users of the "Chaos wheel" were the ones who mentioned the most units (28 %) with the users "Wind mills sub-group 1" (14 %), "Wind mills sub-group 2" (11 %), and the "EV Driver" (10 %), while the users "Hydro-power", "House + Office", "Solar", "Switch", "Factory" and Professor mentioned the least (8 %, 6 %, 5 %, 7 %, 6 % and 5 %, respectively).

We observed an intermediate association between the players' profile and the collaborative actions (Cramer's V2 = 0.05). RD (as stated before, we only report following on associations that exhibited a RD value in absolute terms > 0.25.) analysis reveals a noticeable positive attraction between the "Generation" acts and the "Wind Mills sub-group 1" (RD = +0.39, e.g., "Active electricity flow from zone B to A"), "House + Office" (RD = +0.54, e.g., "Use the hydro-power") and "Factory" (RD = +1.32, e.g., "Use the switch"). "Evaluation" acts were characterized by a strong attraction with the "Wind mills sub-group 1" (RD = +0.62, e.g., "You are doing well"), "Hydro-power" (RD = +0.35, e.g., "Good job"), "Driver" (RD = +0.74, e.g., "Great, guys") and "Solar" (RD = +1.03, e.g., "It is difficult for the solar generator").

Table 3 shows the frequencies detected of the various subject types addressed during the game according to the role of the students and the professor. The subjects are mainly "Procedure" (51 %, e.g., "You need to consume electricity to score points") and "Object" (29 %, e.g., "It is difficult for the solar generator"), and to a less extent, "Goal" (9 %, e.g., "Come

Table 2. Number of collaborative activities detected during the game for the different groups of students and the professor.

	Information	Generation	Evaluation	All
Wind mills sub-group 1	12	4	4	20
Hydro-power student	8	2	2	12
Wind mills sub-group 2	13	1	2	16
House + Office	6	2	1	9
Chaos wheel student	33	6	2	41
EV driver student	10	1	3	14
Solar generation student	5	1	2	8
Switches student	9	0	1	10
Factory student	5	3	1	9
Professor	6	1	0	7
All	107	21	18	146

Table 3. Frequencies detected of the various subject types addressed during the game according to the role of the students and the professor.

7	Object	Solution	Data	Procedure	Goal	Task	All
Wind mills sub-group 1	4	0	0	14	1	1	20
Hydro-power student	4	2	1	5	0	0	12
Wind mills sub-group 2	3	0	0	10	3	0	16
House + Office	3	0	0	4	0	2	9
Chaos wheel student	14	0	2	18	6	1	41
EV driver student	5	1	2	4	2	0	14
Solar generation student	3	0	0	5	0	0	8
Switches student	3	0	0	7	0	0	10
Factory student	2	0	1	4	0	2	9
Professor	2	0	1	3	1	0	7
All	43	3	7	74	13	6	146

on, we are at 78% of state of charge for the battery"), "Data" (5%, e.g., "I am at level 6"), "Task" (4%, e.g., "Use the switch") and "Solution" (2%, e.g., "Put oxygen pressure to 100% to increase the autonomy of the lithium-oxygen powered car"). There was an intermediate association between the players' profile and the collaborative actions (Cramer's V2 = 0.08). RD analysis reveals a noticeable positive attraction between "Object" subjects and "Solar" (RD = +0.27, e.g., "It is difficult for the solar generator"), between "Solution" subjects and "Hydro-power" (RD = +7.11, e.g., "Put oxygen pressure to 100%"). "Data" subjects were characterized by a strong attraction with "Hydro-power" (RD = +0.74, e.g., "Every time I use the hydro-power device you stop it"),

"Driver" (RD = +1.98, e.g., "Remember the cost of using this car"), "Factory" (RD = +1.32, e.g., "There is too much electricity in zone B") and "Professor" (RD = +1.98, e.g., "In which level you are now?"). "Procedure" subjects were characterized by a strong attraction with "Wind Mill sub-group 1" (RD = +0.38, e.g., "Go left") and "Switch" (RD = +0.38, e.g., "Turn in circle in this place"). "Goal" subjects were characterized by a strong attraction with "Wind Mill sub-group 2" (RD = +1.11, e.g., "We are at 185000 points"), "Chaos wheel" (RD = +0.64, e.g., "Come on guys let's get 30000 points"), "Driver" (RD = +0.60, e.g., "What is your score right now?") and "Professor" (RD = +0.60, e.g., "Right now, it is almost 500000 points"). "Task" subjects were characterized by a strong attraction with "House + Office" (RD = +4.41, e.g., "Use the hydro-power!") and "Factory" (RD = +4.41, e.g., "Use the switch").

Overall, these detailed studies have shown that, even if learning outcomes were not better after using Smart Grid MR 2.0, our educative game does not trigger cybersickness. It also brings significant immersion to the students, as well as a high level of presence and user experiences. Smart Grid MR 2.0 also triggers an actual collaboration between students with a pedagogic goal. These collaborative actions and the topics addressed depend on the roles of the students in the game. A significant amount of information transmission between the students is triggered by this collaboration, in particular about the procedures and the sub-goals to be reached to collectively succeed in the mission of reaching an overall score as high as possible in the game.

4. Digital Twin of a Battery Manufacturing Pilot Line: SIMUBAT 4.0

In this section we describe SIMUBAT 4.0, an educative game we have developed to interact with a LIB or sodium-ion battery manufacturing pilot line represented in a VR environment. Such representation is a digital twin of our in house battery manufacturing pilot line, located at the Laboratoire de Réactivité et Chimie des Solides (Université de Picardie Jules Verne and CNRS), in Amiens, France (Figure 13).[40]. All along the game, the player is guided with position markers indicating which manufacturing process step he/she has to undertake, similarly to a GPS-empowered system like Google Map. At the beginning of the game, the player has to go to a board that lists the envisioned LIB cell electrodes chemistries and formulations, electrodes properties (e.g., porosity) and cell energy (Figure 13a). The game contains a database of several of those targets which are proposed randomly at the beginning of each game. Such database is fully configurable and targets can be suppressed or added.

The player proceeds then to the fabrication of a graphite electrode. For this purpose, he/she first has to go near a table (Figure 13b) where he/she has to pick the container of the graphite electrode slurry (made of graphite particles, carbon additive and CMC binder forming a suspension in water) (Figure 13c). The player has then to bring it to the mixing machine (Figure 13d). On the side of this machine, the player finds a control panel (Figure 13e) where he/she has to choose the right mixing parameters values (mixing speed and time) in order to be allowed to start the mixing of the pre-prepared slurry (the so-called pre-mixing process is not represented, for simplicity purposes). The mixing process starts by pressing the start button and is simulated dynamically by the game with a timescale much shorter (a few seconds) instead of the several hours typically used with real mixers, and this for playability purposes. Once the mixing is finished, the player has to take the graphite slurry container and place it near the coating/drying machine (Figure 13f). After finding the correct parameters values (coating speed and comma gap) in the corresponding control panel, the player is allowed to start the coating and drying processes which are animated dynamically by the game (Figure 13g). Then the player has to go to the opposite side of the coating/drying machine and pick the coated current collector (Figure 13h). He/she has then to bring it to the cutting machine (Figure 13i). This machine does not require any parameterization and just need to be launched by the player by pressing the start button available in the corresponding control panel. The player then sees the cutting process of the electrode, consisting of the removal of the excess metallic foil. Once the latter is finished, the player has to take the electrode and put it in the calendering machine (Figure 13j). In the associated control panel, the player has to find the correct parameters values (the gap between the calendering rolls, their temperature and speed) to be allowed to start the calendering process that is simulated by the game dynamically (Figure 13k). Then the player needs to go to the other side of the calendering machine, take the calendered graphite electrode and place it in the winding machine, where a separator band is already placed (Figure 13l). Subsequently the player has to restart the entire process for fabricating a NMC electrode, by going again to the table where there is the NMC electrode slurry container (made of a suspension of NMC active material particles, carbon additive particles and binder in a non-aqueous solvent such as NMP), then to the mixing machine, and so on. The game has different representations of the type of current collector depending if one is addressing the fabrication of a negative electrode (e.g., graphite electrode on a cooper foil) or a positive electrode (e.g., NMC electrode on an aluminum foil)).

Figure 13. Snapshots along the process of our educative game SIMUBAT 4.0.

Afterwards, once the player has placed the NMC electrode in the winding machine, he/she is allowed to start the winding process to manufacture cylindrical cells (18650 format). Then, the player has to take the cell (Figure 14a) and bring it to the welding machine, where the process can be started by pushing on the start button (Figure 14b). Once this is finished, the player has to bring the cell to the electrolyte filling chamber which also contains the crimping machine (Figure 14c). The chamber contains a dryer simulating the water removal from the cell (Figure 14d). The electrolyte filling is then simulated (Figure 14e) followed by the crimping process. Once this process is finished, a robotic arm takes the cell out of the chamber. The player has then to take the cell and bring it to the electrochemical tester (Figure 14f) which shows the achieved cell energy (Figure 14g). The game was primarily developed to be played in a VR environment by using HTC Vive hardware (Figure 14h and i). But in order to maximize the outreach of this game, specially to make the wide public to discover how battery cells are manufactured, we have decided to develop also a version that can be played from an Internet Browser.[41,42] This strategy is similar to the one we have adopted (motivated by the Covid-19 pandemics) with the educative game Tortuosity VR[14] for which we also developed a version that can be played from an Internet Browser that was presented by invitation in the European festival Science is Wonderful! in the year 2020.[43]

5. Possible Implications for R&D

The omnipresence of digitalization in our life is not new: digitalization already allowed the forecasting of human-made or natural systems, the optimization of complex processes, and the simulation of dangerous situations to experiment in real life.[44] We believe that Smart Grid MR 2.0 introduces a digital technology that paves the way towards more collaborative ways to learn and perform research on energy-related topics. We believe that this inherent characteristics of using interconnected objects linked through a central server (a laptop in our case) where the VR environment is managed by continuously receiving inputs from the objects manipulated in the real world, paves the way (through some technical modifications) towards multi-site learning and collaborative work. One can imagine groups of students or researchers located in different geographical regions interacting remotely in real time through our educative game. For instance, one group in one city could

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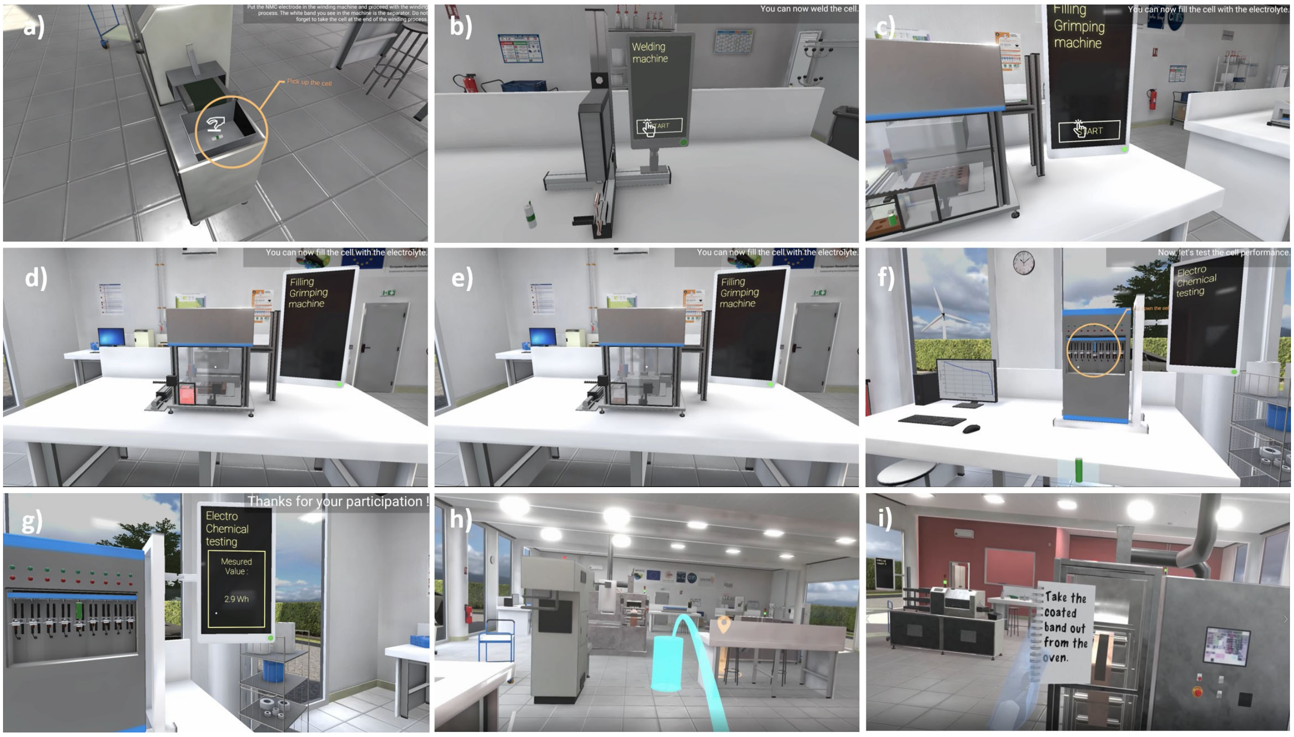

Figure 14. Snapshots along the process of our educative game SIMUBAT 4.0.

be acting on the 3D-printed wind mills, while another group on the electricity distribution switches, and a student located in another city driving the EV in the VR environment. Besides its educational interest, Smart Grid MR 2.0 is a truly multiscale simulator from the battery cell to the EV and the power grid. That means that it can be used to investigate complex interactions between battery technologies, EV driving modes and interplays between electricity generation, distribution, consumption and storage. In that sense, Smart Grid MR 2.0 could find interest as a tool for research. The scripts behind each of the simulated scales being modifiable, researchers could experiment with different battery cell discharge-charge models and/or wind-to-power production ratios or RFB models. Furthermore, the impact of the mechanical aspects of the EV (e.g., mass, friction with road) on its autonomy can be explored thanks to the modular character of Smart Grid MR 2.0.

The "internet-of-things" architecture of our educative game can allow collaborative research by bringing together researchers with different scientific backgrounds (e.g., some focusing on materials science, others on electrical engineering) to collaborate through a single MR environment, being all at the same location or, once again, in different geographical locations (e.g., institutes or cities). This may sound futuristic, but the remote collaboration between scientists in digital environments is becoming a reality. As an example, the software Microsoft Mesh allows persons wearing Hololens 2 Mixed Reality glasses to interact through avatars in the same digital environment.[45] Our platform is different in the sense that interaction with real objects interplays with interactions with the virtual environment, creating a truly mixed environment between reality and virtuality. Moreover, we could also imagine researchers performing scientific research by playing this game.

Our digital twin of the pilot line, SIMUBAT 4.0, paves the way towards a new way of doing battery cell manufacturing simulations. We could imagine machine learning and physics-based models as the ones of the ARTISTIC project,[47] running behind each of the triggered steps by the player. This platform can become also a collaborative environment where several technicians, engineers and scientists can meet through avatars and interact in manufacturing battery cells. This can be performed by a senior technician who remotely interact with trainees about good practices in the manufacturing process. The concept behind SIMUBAT 4.0 could be transferred to other energy-related topics or fields, because this type of training has the potential to help in the transfer of skills in a risk-free environment. For instance, we could imagine to use a similar concept to train on how to handle safely chemicals in a virtual laboratory before handling those chemicals in real conditions.[46] Last but not least, it is worth to mention that SIMUBAT 4.0 constitutes a fully flexible VR environment: more materials, electrode formulations and process steps can be added according to the needs.

6. Conclusions and Perspectives

Games are omnipresent in our world: for diversion, learning, competition and gain. Educative games (also known as serious games) are games designed for learning. If designed properly, they can rise motivation, engagement and learning efficiency of the students/players. They offer an interactive and immersive environment, a necessary condition to achieve high learning rates. Rather than passive observers, trainees engage in those learning environments as active participants.

In this Concept, we presented two new interactive and immersive educative games aiming to popularize the energy storage field: a multi-user multiscale simulator of an electricity grid in Mixed Reality, Smart Grid MR 2.0, and a digital twin of a battery manufacturing pilot line, SIMUBAT 4.0. Smart Grid MR 2.0 consists of a VR environment interacting with real objects which can be manipulated in the real world. The latter represent electricity production devices, electricity consumption entities, devices controlling electricity distribution and an object triggering chaos in the power grid. The VR environment consists of a virtual map where an EV is driven by a player with the mission to collect as much as gifts as possible by escaping from pirate trucks. This EV can be recharged by parking the EV in stations fed with the power coming from the grid. A RFB in the digital world allows for the storage of energy if the power grid is properly managed by the players.

Smart Grid MR 2.0 can be used by up to 16 players simultaneously, constituting a very interesting concept for collaborative learning. Our studies have shown that, even if learning outcomes were not better after using Smart Grid MR 2.0, the latter does not cause cybersickness, bring a high level of immersion, presence and user experiences, and promotes a pedagogical activity characterized by an actual collaboration between students. These collaborative actions and the topics addressed diverge according to the roles of the participants in the game. This collaboration results in a very significant amount of information transmission between the participants, in particular on the procedures and on the subgoals to be reached to collectively succeed in the mission.

Our digital twin of a battery manufacturing pilot line simulates all the steps of electrodes formulation and cylindrical cell manufacturing, from the mixing, to the coating, drying, cutting, calendering, winding, dryer simulating, electrolyte filling, testing and welding, electrolyte filling and electrochemical test. This digital twin is gamified, i.e., the player has to accomplish the mission of manufacturing a cell with the performance proposed at the beginning by the game on a digital board. All along the process steps, the player has to choose the right parameters to perform each of the steps, otherwise he/she is not allowed to proceed further. The purpose of this game is to engage with the large public and students with an introduction to battery manufacturing. This game is playable through any type of Internet Browser just with the keyboard and mouse of a computer.

Perspectives regarding Smart Grid MR 2.0 include the implementation of multiple EVs driven by multiple players in VR that should compete to collect the gifts and for the electricity available to recharge their respective cars. Furthermore, the RFB in the game could become parameterizable, e.g., by allowing the players to choose the chemistries of anolytes and catholytes and/or control the pumping speeds, which may result in different RFB powers and capacities. Smart Grid MR 2.0 also paves the way to investigate different serious playing modes. In the game theory,[48] symmetric games are the games where all the players have the same goals (like in chess), while asymmetric games refer to games where the players do not have the same goals (like in a business). In that regard, we could compare the learning performance by the students under a symmetric scenario in which for instance students in charge of producing the electricity using the wind mills compete with the ones producing electricity by using the solar panel and the water funnel, with the symmetric scenario in which all students play together with the same objective (collecting as many points as possible) as in the study presented in this Concept. In the game theory, a perfectly informed game is defined as a game in which all the players have the information in real time about what is being played (like in chess). In contrast, in an imperfectly informed game, the players do not know the game/strategy of the other players (like in poker). Smart Grid MR 2.0 could be used to explore these two playing modes, for instance, by requesting the students producing electricity to be in a different room from the ones consuming electricity, in a way that they do not see the actions of their pairs but only their consequences of their actions. It is clear that Smart Grid MR 2.0 can be played in a cooperative or non-cooperative way, and that its features can be evolved as a function of the pursued pedagogic objectives.

Perspectives regarding SIMUBAT 4.0 are multifold. First, we plan to organize a series of online competitions between players with the goal of "who is going to fabricate a LIB cell the first?". This will require us to add an extra technical feature allowing to connect online players by pairs or by groups, similarly to classical online adaptations of popular games such as chess. Second, we plan to extend the number of manufacturing recipes in the current version of this educative game, and allow more flexibility for the final electrochemical testing step, by giving the user the possibility to choose C-rates and cycling protocols. Third, we plan to embed surrogate models in each of the virtual machines which predict the properties of the electrodes and cells as a function of the parameters entered in the control panels of these machines. These models will be supported on the ones developed by us in the ARTISTIC project.[49–55] This will allow to perform computational simulations of the battery manufacturing process by interacting in real-time with responsive 3D virtual representations of the machines, and without needing any knowledge on computational aspects. This could pave the way to new approaches to support battery manufacturing digitalization.[56] Furthermore, we plan to extend this digital twin to represent other manufacturing machines (in particular those of battery gigafactories) and less traditional electrode manufacturing processes, such as extrusion or other dry processes. Regarding the former, SIMUBAT 4.0 can constitute a very useful tool to train technicians before their arrival to work in battery gigafactories, to familiarize them with the characteristics of the machines (for instance, the spatial location of their commands, the notions of distances and sizes), the gestures to adopt upon manufacturing electrodes and cells, etc. Finally, we plan to make this environment usable by multiple VR users at the same time, these users

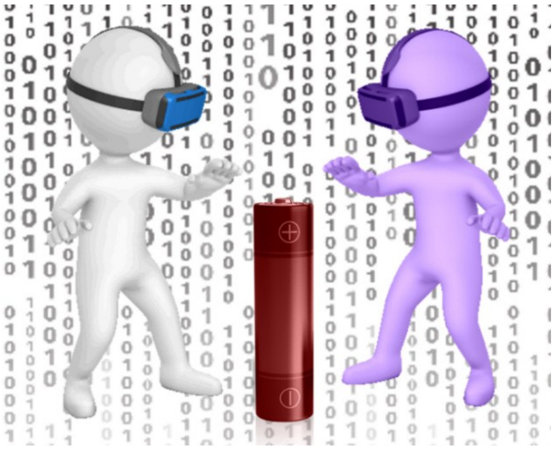

Figure 15. The metaverse for energy storage sciences: an immersive collaborative space for R&D.

being at different locations and represented as avatars. We believe that the ongoing democratization of VR hardware will strongly favor the wide accessibility of these tools by the community. We also believe that our technological concept paves the way to virtual collaborative spaces also for battery manufacturing research and beyond (Figure 15), making the metaverse for energy storage sciences closer than ever before.

Supporting Information

A video illustrating our Smart Grid MR 2.0 educative game in action is provided. A video illustrating the web version of our SIMUBAT 4.0 game in action is also provided. Furthermore, we provide a video illustrating in action the VR version of our SIMUBAT 4.0 game.

The web version of the SIMUBAT 4.0 game can be accessed and played through an Internet browser by clicking in the following link: https://erc-artistic.eu/fileadmin/user_upload/digitaltwin/index.html

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Conflict of Interest

The authors declare no conflict of interest.

Keywords: batteries · digital twin · mixed reality · smart grid · virtual reality

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